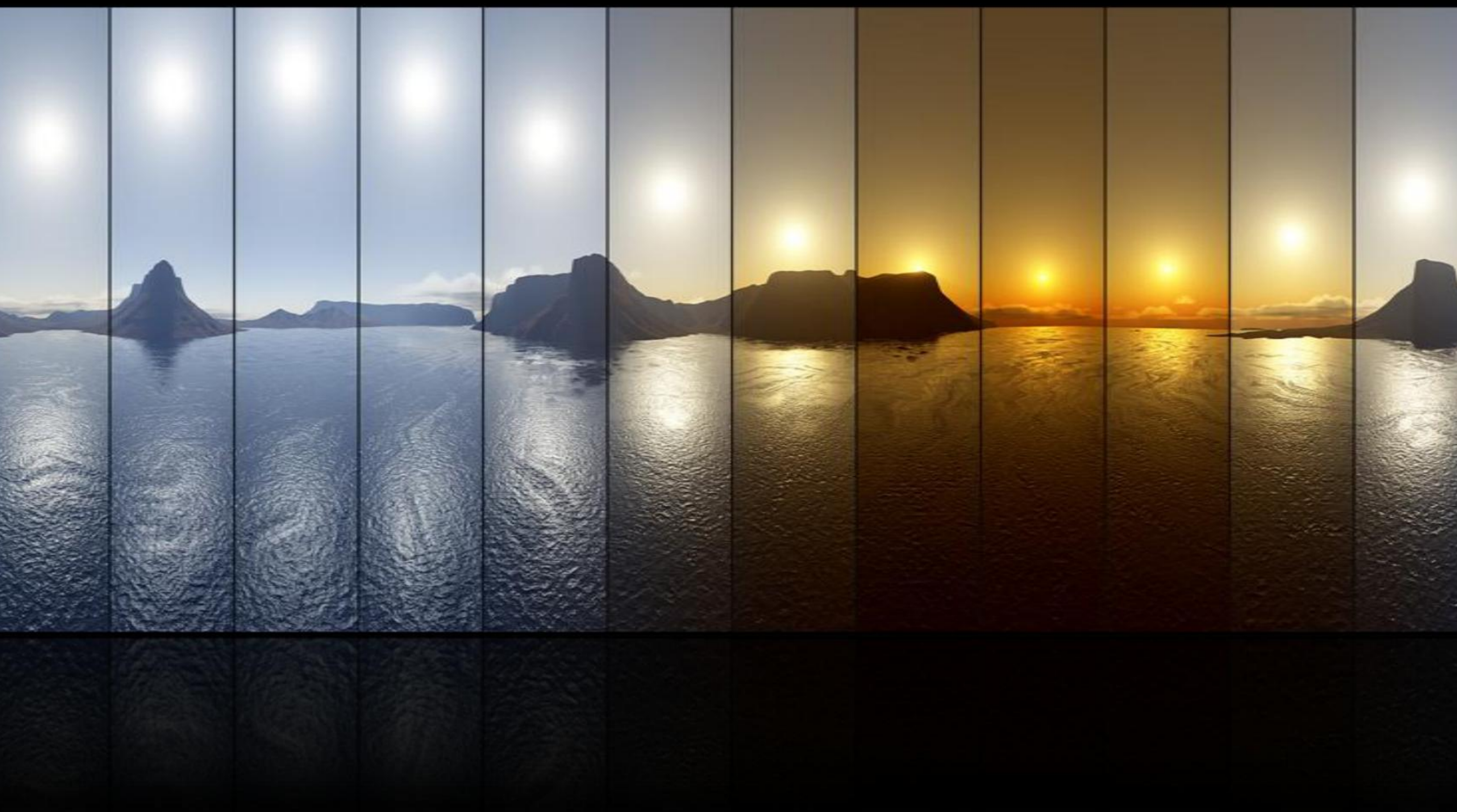
Industrial Solar Energy at Royal DSM

From a Pilot Project to Corporate Strategy



Master Thesis Report

Technical University of Delft

W.J.E. Beneker

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TU Delft

Delft University of Technology

DSM

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Name	*Willem Jan Evert Beneker*
Study number	*1095773*
Email	*wjbeneker@gmail.com*
University	*Technical University of Delft*
Faculty	*Technology, Policy and Management*
Section	*Energy and Industry*
MSc. Programme	*System Engineering, Policy Analysis and Management (SEPAM)*

Graduation Committee

Prof.dr.ir. M.P.C. Weijnen	*TU Delft - Energy and Industry*
dr. ir. L.J. de Vries, M.A.	*TU Delft - Energy and Industry*
dr. J. Barjis	*TU Delft - Systems Engineering*
ir. K. de Glopper	*Royal DSM - Food Specialties*

With special thanks to

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ir. A. Ligtenbarg	*Royal DSM - Global Manufacturing Competence Centre*
ir. C. Mariani	*Royal DSM - Capua, Italy*

In Loving Memory of

Grietje Hendrikje de Vries – Prins

Energy and persistence conquer all things.

Benjamin Franklin 1706 - 1790

People will accept your ideas much more readily if you tell them Benjamin Franklin said it first.

David H. Comins

Education is what survives when what has been learned has been forgotten.

B.F. Skinner 1904 – 1964

Preface

This thesis report is submitted in partial fulfillment of the requirements for a MSc. degree in Systems Engineering, Policy Analysis and Management (SEPAM) at the faculty of Technology Policy and Management of the Technical University of Delft.

Early 2009 Royal DSM gave me the opportunity to work on a thesis project that more than fulfilled my wishes: a project of practical, social and scientific value that presented an intellectual challenge, gave me the opportunity to work in a respected international organization and, last but not least, included a visit to the beautiful south of Italy, where I was welcomed with great hospitality.

This research was characterized by interdisciplinary work that included solar engineering. The field of solar engineering is complex and the reader should note that the author is not a solar engineering expert. In this and other fields of expertise, the author relied heavily on the work of others.

The process of graduation unfortunately did not coincide with the easiest period of my life. Although the lessons sometimes came with difficulty and hardship, I feel that I have learned even more because of this. My tendency to believe that work and private life can be held separate was utterly shattered. More importantly, I learned that this is not always a problem! I sincerely thank the people at DSM, DSM Capua and the Technical University of Delft for their understanding and for the support that I received when my artificial barriers between work and private life fell apart. Without their help, and the support of my family and close friends, I do not think I had any chance of success.

Despite difficulties, I at times greatly enjoyed my graduation process. I learned many lessons, have visited beautiful places and most importantly got to meet and know many interesting people. This writing reflects my research efforts; I hope you find it both valuable and enjoyable!

Willem Jan Evert Beneker

Acknowledgments

I sincerely thank the members of the graduation committee:

- **Chairman Prof.dr.ir. M.P.C. Weijnen**, for her insights and valuable comments that helped me improve this research and at the same time made me realize how incredibly much there is still to learn (without feeling bad about it).
- **First supervisor: Dr.ir. Laurens de Vries,** for his extremely valuable advice concerning almost all aspects of this research and his determination to motivate me to do the best I can.
- **Second Supervisor: Dr. J. Barjis** for his valuable comments from a systems engineering perspective that enabled me to improve the structure and consistency of this writing, the research approach and especially my use of terminology.
- **External Supervisor: ir. Kees de Glopper**, for his valuable advice and his efforts to introduce me to the world of DSM. His motivation to ensure a bright future trough smart application of energy technology at DSM is inspirational.

Additionally I would like to thank two people who are not officially part of the graduation committee but were equally important during this research:

- **ir. Ans Ligtenbarg at DSM GMCC** for giving me the opportunity to work on this project and guiding me during the process.
- **ir. Carlo Mariani at DSM Capua**, who strongly supported me during my research in Italy and also showed me a great panoramic view of *Napels* and introduced me to some seriously good pizza.

Many other people supported me during this research: I would like to thank all people at DSM Capua and Delft for their hospitality and support. Villaume Kal, Business Unit Director Capua, for his insights. Ria Berkhout, management assistant at DSM GMCC for her support. Douwe Joustra who previously worked at Capua and Robbie van Bree, water expert at DSM, for their advice. Dr.ir. Pauline Herder of the TU-Delft for her help with respect to extending the meta-model of design. Daniel van Dijke MSc, for sharing his weather expertise.

I would like to thank my numerous great friends and loved ones; they made my times of study an enjoyable and meaningful adventure but most importantly, I would like to thank my family, especially my mother, father and sister for their unconditional love and support.

Executive Summary

During this research the feasibility of retrofitting a solar energy system to the DSM production facility at Capua, Italy was investigated. The main goal of such a project was to improve DSM's environmental footprint while learning from the experience. The main research question was formulated as:

How can Royal DSM improve its environmental footprint through investment in solar energy at its facility in Capua, Italy?

Main research question

The main research results and the answer to this question can be summarized as follows:

DSM can improve its environmental footprint by investing in a solar assisted Combined Heat and Power (CHP) system at Capua. This, on parabolic-troughs based design that simultaneously delivers electricity and process heat, proved best among many investigated solar technologies. Nonetheless, its expected performance[1] is disappointing and investment is not advised.

Solar Assisted Combined Heat and Power: best solar alternative but not recommended.

Instead, a gas-engine CHP system is recommended. This technology performs well with respect to DSM Capua's objectives but cannot be combined with solar heating. It is expected to result in approximately 50% green house gas emission reduction and has a short payback period (2.5-3.5 years). All investments involve risk but it is important to note that this investment can also be seen as an insurance policy that secures against the risks of energy price volatility. Systems that simultaneously produce electricity, heat, work (for air compression) and cold, are possibly even more attractive but were not investigated in detail.

A Gas-Engine CHP is much more suitable at DSM Capua.

This research suggests that industrial solar energy can be interesting at other DSM locations where conditions are more favorable. Learning value of a pilot project hardly depends on the location. Therefore, a revised strategy including a top-down and structured search for favorable locations is recommended. The identification of key performance drivers and the analysis toolbox that was developed during this study can aid in assessing locations but further research is required for the development of a comprehensive ranking method. Favorable conditions that DSM Capua lacks include: low temperature heat demand and high availability of direct normal radiation.

A top down strategy is advised to search for favorable solar locations.

[1] Simulation shows a Net Present Value of 1.6 M Euro, payback period 8-25+ year and 26% green house gas emission reductions, most of which is caused by gas-firing in the CHP system not by the solar assistance.

Industrial locations with a low temperature heat demand (<100 ^{o}C) are probably more suitable for retrofitting a solar energy system than DSM Capua. Unfortunately the toolbox used to asses DSM Capua was not developed to analyze the performance of low-temperature solar technologies such as evacuated tubes. Adding this ability will probably require an investment in a commercial solar analysis product.

The developed toolbox needs extensions to include low-temp technologies.

Last but not least this research recommends that the investigation of solar investment opportunities becomes part of an integral energy analysis. This analysis should at least include the investigation of energy efficiency improvements because abating energy consumption is generally more cost-effective than implementing renewable energy sources. A solar strategy is merely a quest for implementing a particular technology whereas an integral energy analysis is a quest for fulfilling objectives.

The solar strategy should become part of an integral energy analysis.

Stepwise Approach:

These results were obtained via research and design efforts that involved multiple steps.

Basis of Design

First a basis of design was established to capture client objectives and constraints, describe the design space and the operational environment (exogenous conditions).

Screening

A screening method was used to identify which of the fifteen different solar technologies are potentially interesting at DSM Capua. The screening tests were developed based on physical constraints as well as DSM's objectives. Only four design alternatives passed the screening tests: Photovoltaics (A), Parabolic Troughs for heat generation (B), Solar Assisted Combined Heat and Power (C) finally a non-solar technology was also investigated: CHP without solar assistance (D). Many of the other solar technologies were excluded because they cannot reach sufficient operating temperatures[1]. The availability of direct normal radiation[2] at Capua unfortunately proved limited; this in part seems to be caused by the proximity of the Mediterranean Sea and the Vesuvius.

Model Development

During this research a system dynamics model (using Powersim) was developed to assess the economic and ecological performance of solar energy (and CHP) systems retrofitted to the industrial process at DSM. The tool's purpose

[1]The DSM facility has is no net heat demand below 100^{o}C.

[2] Direct normal radiation comes directly from the direction of the sun and is not scattered by the atmosphere / clouds.

is to translate the output of solar energy modeling tools into performance indicators that are important to DSM. The model is able to cope with different energy price scenarios, subsidy schemes, feedback tariffs, discount rates, etc. It can perform risk assessments by calculating (and graphing) confidence intervals based on stochastic assumptions and it can additionally use evolutionary optimization algorithms to calculate the optimal scale of an investment (if there is an optimum). This model can be extended to asses solar energy systems at other locations. Albeit this requires the additional use of tools such as NREL-SAM[1] or TRNSYS[2], to predict the solar system's energy output at those locations location.

Testing & Selection

Detailed modeling of the energy systems that passed the screening test showed that the performance of a SA-CHP system (C) proved best among all solar technologies (see Table 1). However, its performance was still regarded unsatisfactory with an 8 to 25+ year payback period and 26% Green House Gas (GHG) emissions reduction[3]. This report recommends that DSM does NOT invest in solar energy at Capua, due to the risk of a long payback period and the availability of a better alternative.

The performance of (D) a CHP system based on a gas engine (that cannot be combined with solar preheating) proved interesting. It has an expected payback period between 2.5 and 3.5 years and can achieve up to 50% CO_2 emission reductions.

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[1] National Renewable Energy Laboratory’s Solar Advisory Model.

[2] Transient Energy System Simulation Tool

[3] Emissions and cost reductions are calculated relative to business as usual.

Table 1, Simulation Results Overview

		Investment	NPV[1]	PBP[2]	GHG red.	GHG red.
		M. Euro	*M. Euro*	*year*	*% of BAU*	*tCO_{2eq}/yr*
A	Flat Plate PV	3.5	0.5	12-19	1.6	602
B	Parabolic Trough Thermal	3.1	-1.5	NA	1.7	639
C	SA-CHP (5MW total)	3.3	1.6	8-25+[3]	26	9.776
D	CHP (6.5 MW total)	3.0	7.7	2.5-3.5	51	19.176

Simulation Results

Investment recommendation

A clear investment recommendation cannot be given without information about mutually exclusive projects, funding and especially production projections. These are all outside the research scope. It is important to note that this investment in CHP can be seen as insurance policy, an investment at fixed costs that reduces the sensitivity to exogenous conditions. Therefore, it is the researcher's opinion that DSM, when assessing the investment opportunity, should focus on the reduced dependence of the total facility on energy price volatility as opposed to only the risk that directly relates to the investment.

Reflection on research scope

The initial scope of this research: "solar energy", was a bit too narrow, as a non solar technology proved a much better fit given DSM's objectives. A broad energy (and market) analysis (that is not technology-specific) of production locations is recommended to prevent excluding interesting technologies due to research scope. Such an integral analysis can help to identify opportunities for efficiency improvements, determine the applicability of CHP, renewable energy sources and energy acquisition strategies (contractual arrangements). Companywide standardization of this analysis additionally creates opportunities for benchmarking the energy related performance of different production locations[4].

Solar Strategy at DSM General

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[1] Average result of Monte Carlo Simulations, 8-12% Weighted Average Cost of Capital (discount rate).

[2] 90% confidence interval

[3] 25+ means longer than life-span and simulation period

[4] Because more technologies become available and conditions change over time, these studies need to be updated periodically.

The research additionally recommends that DSM General develops a strategy to improve the chances of successfully implementing solar energy. Results suggest that choosing an appropriate location for solar energy can be difficult and therefore this research recommends a structured search for favorable conditions and ranking DSM production locations, after which research effort can be directed to the top locations. The analysis tool developed during this study can be used to help find and investigate top locations. Subsequent research is needed in order to define a proper ranking and assessment method but the factors that this research deemed most important are:

- Low temperature, high volume heat demand
- High availability of direct beam radiation (and small seasonal variations)
- High Fossil Fuel Prices
- Subsidies (fixed, mandatory feedback tariffs, tax reductions, CO_2 trading, etc)

Figure 1 and 2 show the availability of direct beam radiation and global radiation. Although a yearly average is only a rough indicator, it was used to illustrate potentially interesting locations for implementing solar energy. Red circles on figure 1 are used to mark locations where solar might be interesting to provide heat below 100°C. Figure 2 on the other hand shows only the locations where concentrating technologies might be applied to yield higher temperatures. The figures illustrate that the inability of concentrating solar systems to utilize anything other than direct beam radiation has wide consequences for both the applicability of solar energy at Capua as well as for DSM General's solar strategy.

Finally yet importantly, it is the researcher's opinion that the investigation of solar investment opportunities should become part of the previously mentioned integral, non-technology specific, energy analysis. Thereby the chances increase of fitting an appropriate solution, technical or otherwise, to identified problems.

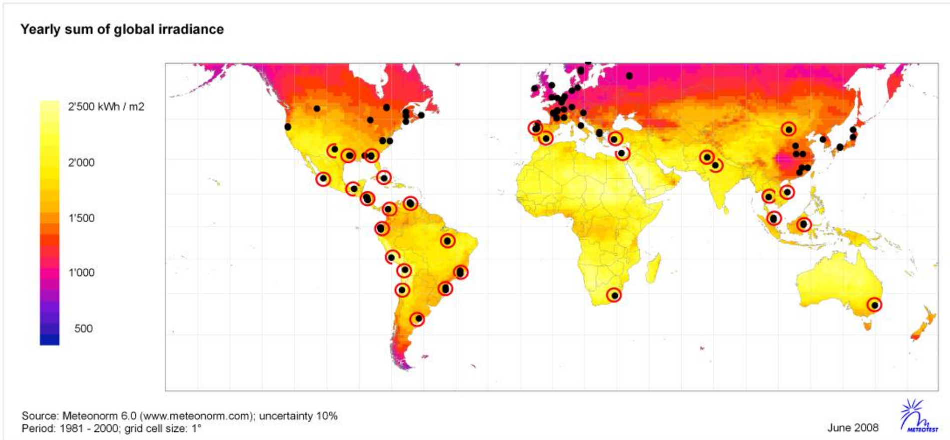


Figure 1, Global irradiance & DSM production locations (dots). Locations where flat plate PV or low temperature heat collectors seem favorable are circled (illustrative only)

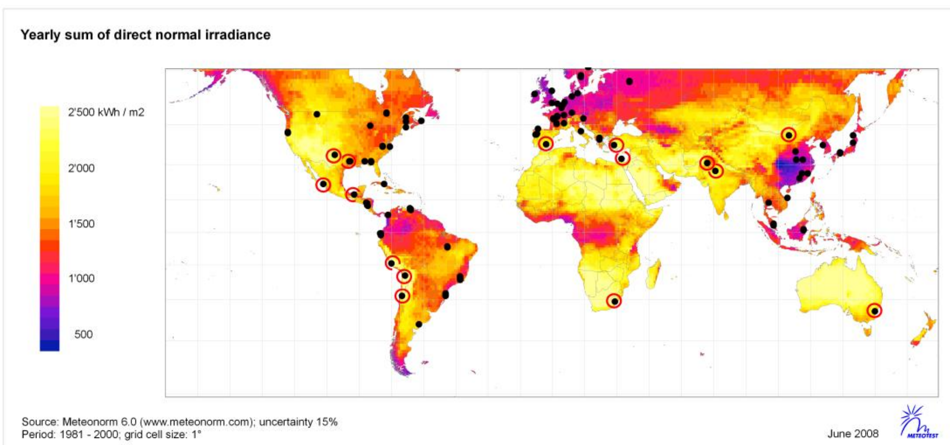


Figure 2, Direct normal (beam) irradiance & DSM production locations (dots). Locations where concentrating technologies might be applicable are circled (illustrative only)

Abbreviations

BAU	Business As Usual
BOD	Basis of Design
CDCF	Cumulative Discounted Cash flow
CHP	Combined Heat and Power
C-PV	Concentrated Photovoltaics
Elec.	Electricity
ETC	Evacuated Tube Collector
GHG	Green House Gas
IRR	Internal Rate of Return
KPD	Key performance Driver
KPI	Key Performance Indicator
LFC	Linear Fresnel Collector
MRQ	Main Research Question
NG	Natural Gas
NPV	Net Present Value
PBP	Payback Period
PT	Parabolic trough
PTC	Parabolic trough collector
PV	Photovoltaics
PV-T Hybrid	Photovoltaic - Thermal Hybrid
RET	Renewable Energy Technology
SA-CHP	Solar Assisted Combined Heat and Power
SF	Solar Furnace
SP	Solar Pond
S-refrigeration	Solar refrigeration
STEG	Solar Thermal Electricity Generation
TMY	Typical Meteorological Year
WACC	Weighted Average Cost of Capital

Contents at a Glance

Table of Contents

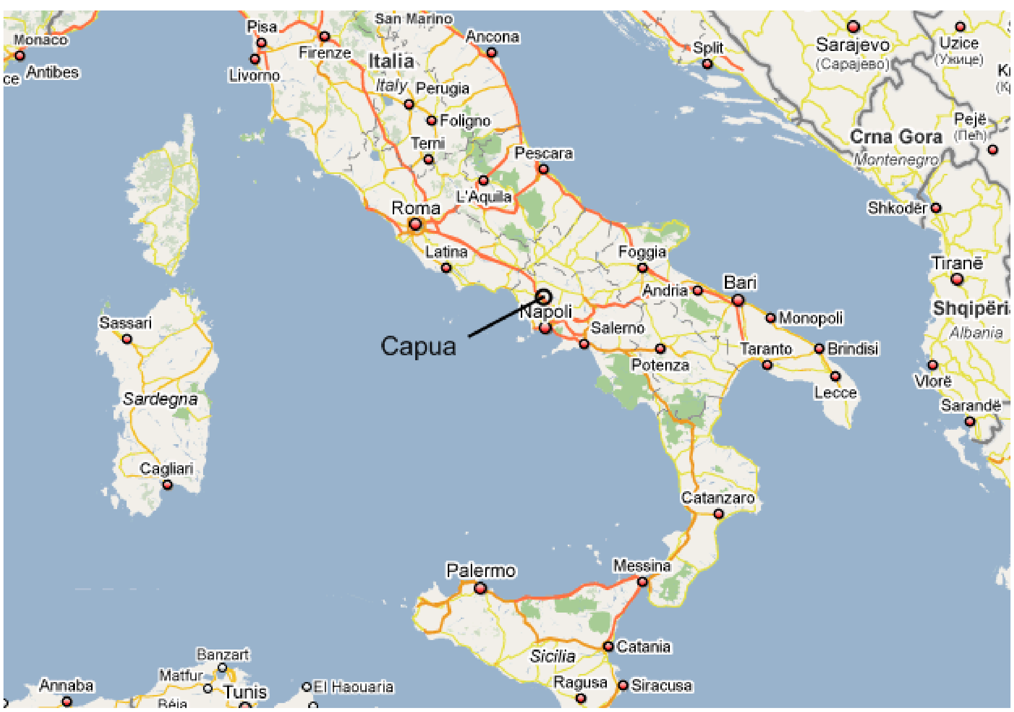
PART I : Problem Exploration

Chapter 1. Introduction

1.1 Problem Outline

What is this report about?

This report is about assessing the potential of solar energy at Royal DSM by investigating the viability of a solar energy project at DSM Capua, Italy. This project was initiated by people within DSM[1] who are interested in the potential of solar energy to fulfill the energy demand of the company's various facilities all over the world. This study, however, was focused on the DSM production facility at Capua only. The performance of solar energy systems is heavily dependent on local conditions, such as radiation levels over time, humidity, local energy price, etc. One of the insights from this research was the identification of the many factors that affect solar investment decisions. This, at one point during the research, caused the realization that DSM General was in need of a different approach towards solar energy. Although generalizations of results based on one case study is potentially unreliable the focus of this research was somewhat redirected towards translating the insights that were gained during the case study into recommendations for a more structured solar strategy.



[1] Specificly Kees de Glopper & Ans Ligtenbarg

Figure 3: Capua, Italy (Google Maps)

1.2 Relevance

Why is this report needed?

Although the difficulties in assessing the performance of a solar energy system at Capua were the initiator of this research, with the wisdom of hindsight it can be stated that this research was valuable for other reasons as well. These are discussed briefly.

Performance of Solar technologies at Capua unclear

Firstly this research was needed and initiated because the performance and applicability of solar technology at the DSM Capua production location is not obvious. Many forms of solar energy systems exist but the performance of each under the local conditions is unclear. Therefore technology choice and rough estimates of technical and economic performance are difficult to make. More information was required to be able to make a well informed investment decision.

Need for revised Corporate Solar Strategy

Second: during the research it became clear that DSM General has an opportunity to develop a structured strategy that could greatly increase the chances of successfully implementing solar technology to fulfill the company's objectives with respect to the environment and economics. The insights gained during the DSM Capua case study proved valuable for developing this corporate strategy.

Knowledge gap in literature

Third: Developing a corporate strategy based on insights into the interaction between local conditions and solar technologies seems an area that has little coverage in scientific literature. This research at the least illustrates that it could be beneficial for companies when researchers develop a wider knowledgebase for corporate strategies that help them to utilize industrial solar technology.

Demand for custom fit analysis tool

Fourth: During the research DSM became interested in adapting the method and tools that were used to investigate DSM Capua so that they could be applied to other DSM production locations to assess the applicability of solar (and Combined Heat and Power) technology there as well. This research involved the development of such a tool. Most existing tools are either very complex, do not directly apply to industrial application or cannot calculate the performance indicators that DSM deems important.[1]

[1] Only tools that are freely available for academic use are considered during this study, unless otherwise noted.

1.3 Background

Solar Energy Technology in Context

Proved reserves of oil and gas, at current rates of consumption, would be adequate to meet demand for another 40 and 60 years, respectively. The reserves for coal are in better situation as they would be adequate for at least the next 250 years (Kalogirou 2004).

Energy on the political agenda

Rising fuel prices and increased environmental concerns caused a worldwide search for efficiency improvements and alternative energy sources. Reasons for most western countries to try to move away from fossil fuels include global warming, import dependency, costs and price uncertainty and security of supply. The World Energy Outlook of 2007 stated: *"The challenge for all countries is to put in motion a transition to a more secure, lower-carbon energy system, without undermining economic and social development."* (IEA 2007)

Economic Shock

And recovery

Recognizing that alternative energy sources are in an early stage of technical development and improvements were needed in order for these technologies to become economically attractive, a multitude of publicly funded projects and organizations arose. The basic idea behind most of these projects is to stimulate the technical development of renewables until the respective industries become self-reliant, and further market penetration becomes automatic as customers choose renewables over fossil fuels. The price of fossil fuels has recently dropped due to a sudden economic shock and predicting the development of energy demand and supply has become increasingly difficult.

Renewable Energy Economics

Although from an economic perspective, renewables have lost position relative to fossil fuels, it seems that public and political support for renewables has not reduced momentum. In addition, many believe that due to market fundamentals, that is; reserves decrease and the world population grows (and India and China gain economic strength) energy prices will increase in the long term. The question is: when? On the other hand: how long can this political momentum go upstream against the realization that in a time of expensive credit, money is spent to reduce the use of a source of energy that is currently cheaper? Possibly the credit crunch itself has reduced the tendency to favor short term over long term benefits.

Cost Developments

Public and private initiatives have already reaped results from these stimulating policies. As Figure 4 illustrates renewable technologies have seen a major development in recent years. Solar energy prices have significantly reduced, more and more technologies are commercially available, are well tested and have predictable performance. Examples are not hard to find: solar heaters are used throughout China for residential heating, concentrated solar energy parks are in operation in the USA (California, Nevada) and Spain, photovoltaic systems are in use at many remote locations, etc, etc. At the same time Appendix A shows that the capital costs of solar technologies remain high compared to other technologies.

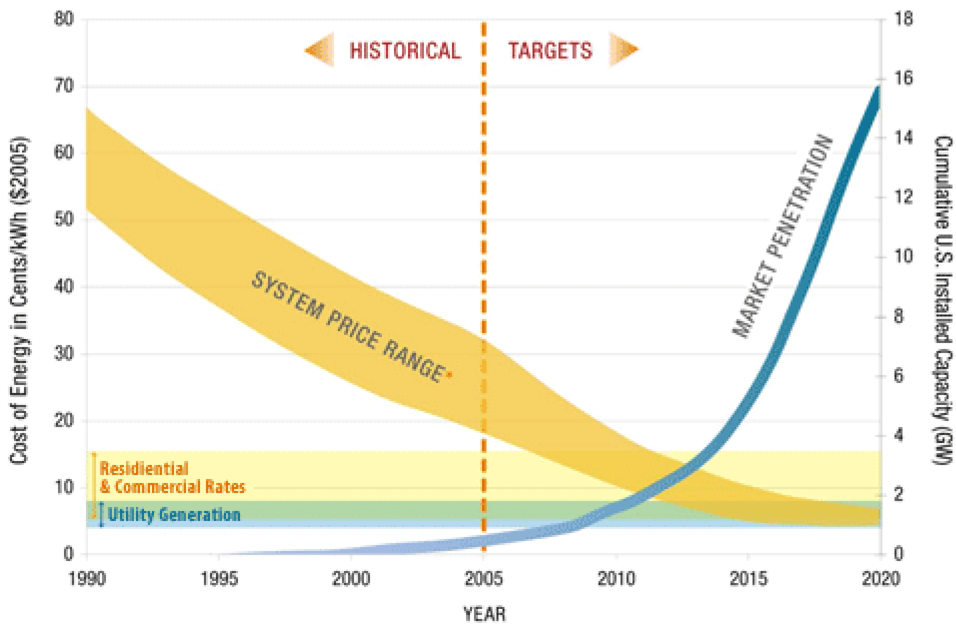


Figure 4, Solar PV costs data and projections as of 2005 (sunenergyfacts.com 2009).

Solar power at DSM

DSM has already taken a very important step, namely recognizing the potential of solar energy. This might seem a bit exaggerated at first but consider that ESTIF (European Solar Thermal Industry Federation) created a list of barriers for growth of solar energy for Industrial Processes and the first item reads the following: *"Awareness: The number of solar thermal installations for industrial processes is very small, and most decision makers in relevant industries have never heard of, or even seen, a SHIP (edit- Solar Heat for Industrial Processes) system. This is a key barrier to the broad adoption of SHIP"* (ESTIF 2006) Some of the examples of renewable success-stories presented earlier are somewhat special. These systems are able to compete with fossil fuels due the 'special' conditions under which they operate. For example: the concentrated solar energy plants in the USA and Spain are able to compete with fossil fuels because they generate maximum electricity exactly when prices are high: during air-conditioning induced peak demand. Photovoltaics are often used in remote locations where a grid connection is impossible or very expensive. In other cases these 'special conditions' are created by policy, high mandatory feed-back prices that operators are obliged to pay for renewables for example. Having said that renewables in general and solar energy specifically are in an early stage of development and are often utilized in niche markets, technical development, political awareness and the incorporation external costs create more and more viable opportunities. In a sense, this study investigates whether the conditions at DSM Capua are sufficiently favorable for implementation of a solar energy technology.

1.4 The Client: Royal DSM

For whom is this research intended?

Royal DSM is a multinational producer of food specialties, pharmacy and several other categories of products. The company is research intensive and makes many high tech products. Many of these products are produced via fermentation: a process where microorganisms convert some feedstock into a product. Contamination risk and the sensitivity of this highly engineered microorganism to external factors make the process rather complex. However, from an energy perspective it is rather simple. The fermentation reaction is a batch process that requires cooling (as the micro-organism induced reaction are exothermic), more cooling is required for down-stream processing, heat is required for sterilization, and large amounts of electricity are required for air compression (required for aerobic fermentation) and downstream processes.

Sustainability is high on DSM's agenda. DSM has had a consecutive high ranking on Dow Jones Sustainability Index. Recently various people at DSM initiated and fertilized the idea to use solar energy to power their industrial processes. This originated from the realization that solar energy is by far the most abundant energy resource on the planet and the fact that many of DSM's production facilities reside in sunny areas. Several students were attracted in order to investigate solar energy options at DSM, of which I am one. I was asked to imagine myself as an entrepreneur who had the opportunity to sell DSM a solar energy project at DSM Capua, Italy.

What does the client want and how did this affect the research questions & scope?

This section aims to briefly clarify the preliminary goals of DSM with respect to this project, to be able to present how my understanding of the client's objectives led to the research questions that will be defined in the next section. However during the research a more detailed study of stakeholder(s) was carried out as well in order to define objectives and key performance indicators. For now it is important to note that the following factors were considered when defining the research questions.

- First and foremost DSM is interested in the investigation of solar energy. Broadening the scope to include other RES (renewable energy systems) such as wind has been discussed but was mostly rejected. DSM wished to keep the research scope limited in favor of depth.
- DSM is interested in starting a solar pilot project; the scope of this research is limited to investigating the possibilities at Capua, Italy. Nonetheless it was recognized that the insights gained can be valuable when considering other locations.
- DSM is a large company divided in sections of various degrees of autonomy. An uneven distribution of risk and benefits over these divisions can potentially create conflicting interests within DSM.
- In a late stage of the study the scope of this research somewhat shifted towards a solar strategy instead of a solar pilot project at DSM Capua for reasons that will soon become clear.

1.5 Research Questions

What questions does this research intend to answer?

Although people at DSM suspect there is a potential for RES and specifically solar energy to supply part of its energy demand (and thereby improve the company's environmental footprint) there is not enough direct knowledge available about the applicability of solar energy at specific locations or about appropriate methods to determine this. Combining this with the focus on Capua led to the following main research question (MRQ), and sub questions (1-9).

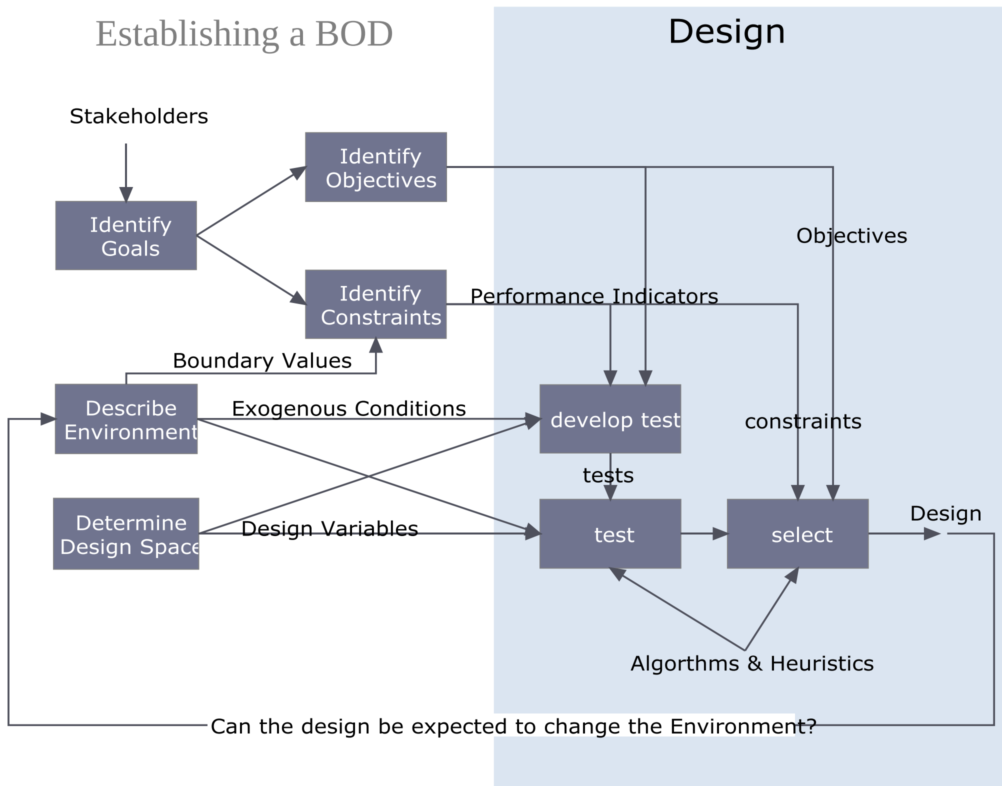
MRQ: How can Royal DSM improve its environmental footprint through investment in solar energy at its facility in Capua, Italy?

1. *What are the objectives and constraints of DSM?*
2. *Which solar design alternatives are available for industrial application and what are the key factors that determine their performance and applicability?*
3. *What are the relevant conditions for solar energy at DSM Capua?*
4. *Which solar design alternatives can be excluded from further analysis given the constraints?*
5. *What simulation toolbox can be developed to adequately estimate the performance of the selected design alternatives*
6. *How do the selected design alternatives perform at Capua with respect to the objectives?*
7. *Which design alternative is most attractive for DSM Capua? (including Business as Usual)*
8. *How can the insights gained during this research be used to develop a corporate solar strategy?*

1.6 Research Approach

The research can be separated into two main parts; establishing a Basis of Design (BOD) and Design. Each part includes several research activities as is depicted in figure 5 below.

How is the problem tackled?



Report Structure:

Part I: Introduction

Part II: BOD

Part III Design

Part IV: Conclusions

Figure 5, Adapted Meta Model of Design

This division between BOD and design and many of the research questions are analogue to the *meta-model of design* that was developed at the TPM faculty by Herder & Stikkelman. The meta-model presents a structured view on the design process. Designing is often an iterative process and the model must not be seen as a step by step guideline, it rather depicts the various design activities that need to be performed and how they relate. The model was used to structure both the research itself as well as this report. The original meta-model of design however was adapted by the researcher. The activity *"describe environment"* was added after discussion with the original author (-Herder) to better fit the needs of this research.

A BOD defines what a design is set to achieve, defines how to measure performance, defines when a design is acceptable, defines what design space will be considered and additionally presents under what assumptions about the operating environment the tests will be conducted. Establishing BOD includes the investigation of literature in order to discover the available technologies and the factors that influence their performance, and subsequently describe the situation at Capua regarding these factors.

An (adapted) Meta model of design is used as a framework for research and structured writing.

The second part of the project is the design part. This part requires the designer and stakeholder to make choices based on their preferences. Therefore this process can be regarded more subjective than that of establishing the BOD. Models and estimation methods will be applied to predict the performance of the various alternatives under the specific conditions at Capua relative to the objectives and within the constraints, that all followed from the BOD. Once an estimation of the performance of the alternatives is made, one or two will be chosen with the help of a multi-criteria decision analysis. A business case will be constructed for the selected alternative(s) in order to assess the economic viability in more detail. This will ultimately lead to an investment recommendation.

With the wisdom of hindsight it can be said that this research involved designing two separate artifacts: first a solar energy system for DSM Capua and second a corporate solar implementation strategy. The design of the strategy however was limited in time and not all design activities were conducted. For example no tests were developed to test the performance of various strategies.

1.7 Expected Results & Deliverables

This report aims to present a system design for a solar based energy system that provides process heat and possibly electricity that supports the industrial processes of an existing plant at Capua Italy. But what is meant by system? A useful description is given by (Maier and Rechtin, 2002 NOG TOEVOEGEN) *“Systems are collections of different things which together produce results unachievable by the elements alone.”*

Systems Design

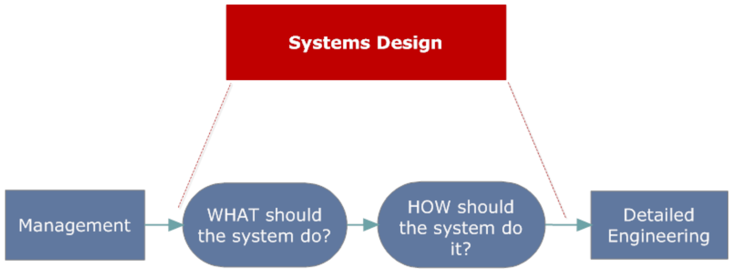


Figure 6, Systems Design

In this particular case the design does not go into detail when it comes to the components themselves; neither will it propose technical improvements to solar collectors nor present more efficient storage techniques. Instead, this systems design is concerned with how to choose and combine systems and components, in order to create a system that best fits the objectives of the stakeholder(s). In essence this report is aimed at translating the views of DSM into a clear description of WHAT the system should do. And once this is made clear, the research aims to describe HOW the system should do this. This research will thus not result in a design for Capua that can directly be shipped to a manufacturer but in a high level design that includes the following:

- A choice from a wide range of solar energy technologies.
- Recommendations on the selection of the main system components.
- Recommendations on how to integrate the technology in the current production system,
- Prediction of the performance of the design, economic and otherwise.
- Recommendation on the implementation path of a pilot project.

In addition, the report makes recommendations towards a corporate solar strategy that includes

- Identification of the factors that are important when assessing other DSM production locations, technical, economic or otherwise,
- Suggestions for which DSM production location reside in areas with favorable weather condition exist for various technology types.
- Suggestions for how a solar strategy should be incorporated in an integral energy analysis.
- Suggestions on how the model, that was developed to assess the situation at Capua, can be used to investigate other locations.

These results and the information gathered during this research are transferred to the client via a Public Report & Appendix and a digital file containing the Software Models and Manuals

Chapter 2. Introduction to Solar Engineering

This chapter provides an introduction to solar engineering by discussing the main technological options and choices. Often the drawbacks of a particular technology are attempted to be resolved by a more advanced technology. Unfortunately such new technology comes with other drawbacks. This introduction is written to clarify the main choices and their pros and cons, and illustrate how technical solutions to drawbacks create new drawbacks. Some problems and effects are fundamental to the use of solar energy and cannot be resolved by better technology. In other cases technical development can be expected to improve performance.

In solar energy literature authors often use different terms for the same concepts and sometimes different terms refer to minor differences that are not important for this research. To clarify and avoid ambiguity the table below presents some of the terminology that was used throughout this research and, if applicable, the synonyms that can be found in solar energy literature (sometimes the tables and figures within this writing use these synonyms because they originate from literature).

term	synonym	description
Solar Energy System		Collection of components that together collects solar radiation and delivers a usable form of energy
Solar Collector		Component that collects the radiation, excluding tracking, transport, etc.
Solar Energy Technology		Group of solar energy systems that rely on the same underlying operating principle
(Solar) radiation	Irradiation, insolation	All radiation from the sun including the visible spectrum of light
Diffuse radiation		Radiation scattered by the atmosphere/clouds.
Direct normal radiation	Direct radiation, Normal radiation, Beam radiation	Radiation directly from the direction of the sun, thus not scattered by the atmosphere.
Tracking system		System that tracks the motion of the sun

Stationary system	static	System that does not track the motion of the sun, but can sometimes be adjusted seasonally by hand.
Concentrating system		System that relies on concentrating the solar radiation before absorbing it.

2.1 Solar Systems Categorizations

A distinction can be made between *solar energy systems* and *solar collectors*. The solar collector is the subsystem that collects the radiation. Depending on the type of technology solar systems often include other components that are vital for operation. Examples are a mounting system, heat transfer fluid systems, invertors, measurements & control, and tracking components. The importance of this distinction is illustrated by the fact that mainstream media often only report the costs of the collectors. Because collectors cannot operate without other system components, this can be quite misleading.

Electric vs. Thermal systems

PV systems produce electricity directly.

Thermal systems can produce heat directly or electricity /cold /work indirectly

Solar energy systems come in various shapes and sizes. A clear distinction is that between Photovoltaic and Thermal systems. Photovoltaic collectors produce direct current electricity which is often converted to alternating current using invertors. Thermal systems produce heat in the form of hot water or steam. Commonly a distinction is also made between active and passive thermal systems (Duffie and Beckman 1980). Passive systems are those that are based on natural convection, this includes for example building design and glazing in such a way that less auxiliary cooling and heating is required over its lifetime. This research however only includes active systems. Heat can either be used directly or converted into work, electricity or cooling.

In addition there are also systems known as Dish Sterling Engines (DSE) and Solar Furnaces (SF) that fall in neither category. DSE's use concentrated sunlight to generate high temperature heat that is converted into electricity by what is known as a sterling engine and a generator that are integrated into the collector itself. SF's are not widely used but refer to systems where light is concentrated directly into chambers where a drying process or chemical process takes place without conversion to steam or any other heat carrier. Last but not least there are also photovoltaic- thermal hybrid systems (PV-T hybrid). These systems are composed of PV panels that produce electricity fused to thermal collectors that absorb part of the energy that is not converted into electricity, and thereby try to achieve higher efficiencies

(Kalogirou, 2007).

Stationary vs. Tracking Systems

Another common distinction that is often made is between stationary and tracking systems. Stationary systems are those with fixed positions that are sometimes manually adjusted each season. (Kalogirou, 2004) The orientation of stationary systems can be chosen to achieve maximum power production, but also to maximize economic value. This is not necessarily the same as the timing of electricity production can be important due to quickly varying market prices. Tracking systems are those that continually track the motion of the sun and correct the position of the collectors accordingly. Depending on the collector type the accuracy of the tracking system can have an enormous effect on the energy delivery (as will be explained shortly). Some collectors thus need highly accurate and therefore expensive measurement and positioning systems.

Flat plate vs. Concentrating Systems

The last clear categorization that is discussed is the distinction between flat plate and concentrating systems. (Quaschning 2005; Goswami, Reddy et al. 2007) Flat plate systems (either photovoltaic or thermal) directly utilize the incoming radiation, producing heat or electricity.

Concentrating systems on the other hand are composed of some type of reflector or lens that is separate from the absorber-surface. The surface of the reflector or lens is known as the aperture area. Its purpose is to focus the radiation hitting it, onto the absorber. The absorber then converts the radiation into electricity and heat (or even both in case of PV-T hybrids). The purpose of focusing is twofold; first it allows for a smaller absorber area and thereby lower investment costs, secondly in the case of thermal systems the lower heat dissipation allows for higher achievable temperatures and efficiencies.

Concentration results in smaller heat-loss surfaces, higher efficiency and higher maximum temperatures

Concentration Ratio

Solar Collectors can also be characterized by their concentration ratio, a measure of the optical concentration of radiation before absorption/utilization.

The ratio between the aperture area and the absorber area is known as the concentration ratio.

Concentrating solar collectors such as parabolic troughs or Heliostat field collectors with a central receiver, vary in the method that is used to reflect the radiation onto the receiver, the tracking mechanism or the shape the receiver itself.

Another useful way to characterize solar energy systems, regardless of the concentration method, is by the *concentration ratio*. This is defined as the ratio between the aperture area and the absorber area (Duffie and Beckman 1980; Kalogirou 2004; Quaschning 2005). For example: a flat plate collector does not concentrate radiation: the aperture area and absorber area are the same, resulting in a concentration ratio of 1. Figure 7 shows typical concentration ratios for various collector types.

Motion	Collector type	Absorber type	Concentration ratio	Indicative temperature range (°C)
Stationary	Flat plate collector	Flat	1	30–80
	Evacuated tube collector	Flat	1	50–200
	Compound parabolic collector	Tubular	1–5	60–240
Single-axis tracking			5–15	60–300
	Linear Fresnel reflector	Tubular	10–40	60–250
	Parabolic trough collector	Tubular	15–45	60–300
	Cylindrical trough collector	Tubular	10–50	60–300
Two-axes tracking	Parabolic dish reflector	Point	100–1000	100–500
	Heliostat field collector	Point	100–1500	150–2000

Figure 7, collector characteristics.(Kalogirou 2004)

Simply creating smaller absorbers in comparison to the aperture area thus enables one to achieve higher temperatures and/or lower investment costs! Unfortunately there are downsides to concentration as well.

Note that technologies such as Linear Fresnel and Parabolic Troughs are based on single-axis tracking where the absorber is a pipe or tube on which radiation is reflected over its entire length (therefore sometimes referred to as line-collectors). Parabolic Dishes and Heliostat Field Collector systems reflect light onto a single point, and require two-axis tracking. As stated before the accuracy of the tracking system can have a large effect on the efficiency of the system. The smaller the absorber area the more difficult it becomes to focus the light on that exact spot during the day.

2 axis tracking is more difficult then 1-axis tracking but allows for much higher concentration ratios.

Lets define the angle between the normal (perfect) angle of incoming solar radiation on a collector and the actual angle (including inaccuracies) as the angle of incidence (i.e. the out of focus angle).

As the angle of incidence strays from zero the efficiency of a collector drops as more and more light is simply not reflected to the right position. The higher the concentration ratio of a collector the less forgiving it becomes. The effect of increasing inaccuracy is illustrated for a parabolic trough collector in Figure 8.

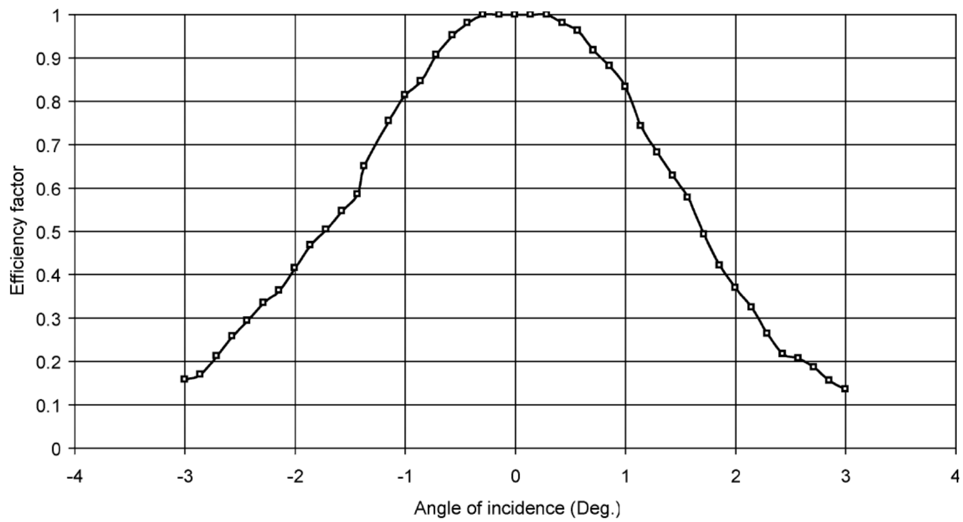


Figure 8, Effect of incidence angle on efficiency (Kalogirou 2004)

Small errors quickly reduce the efficiency of high concentration systems

The angle of acceptance is the angle relative to the normal at which a collector still accepts a reasonable amount of incoming radiation (often defined as 98%). There is a theoretical limit to the concentration ratio caused by the area of the sun as seen from the earth. Above this ratio the acceptance angle of the extreme collector becomes so small that a portion of radiation coming from the sides of the sun (as seen from the earth) is cut off even if perfect accuracy is achieved (Duffie and Beckman 1980).

The first problem with concentration is thus that inaccuracies in tracking the sun and inaccuracies in the absorbers, reflectors or lenses cause a rapid decline in efficiency. A typical PTC with 1-axis tracking already loses 60% efficiency when it is only 2 degrees out of focus. Simulation packages that predict solar performance often include stochastic variables to account for the losses due to tracking inaccuracies (for example ,TRNSYS & NREL SAM).

2.2 Sensitivity to external factors

Weather Effects

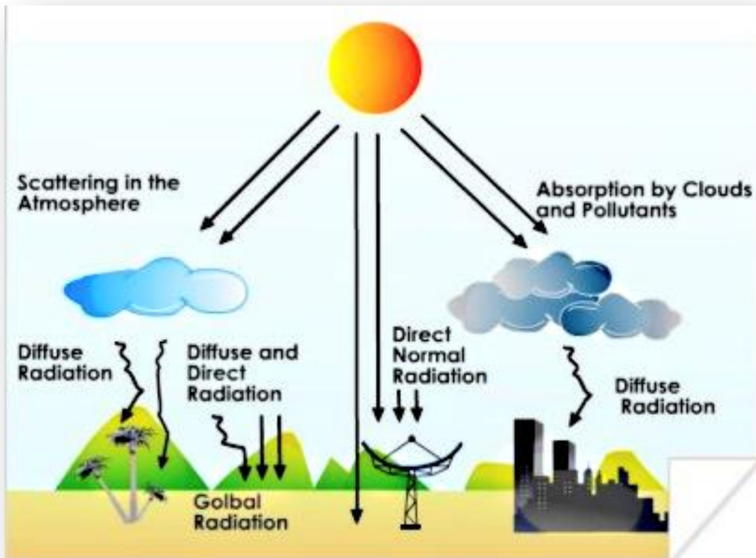


Figure 9, Direct normal (beam), Diffuse, and Global radiation (Ener-t 2009).

If accuracy was the only problem of concentration better technologies could be a solution in the future, unfortunately there is another important factor: weather conditions. Whereas the incoming radiation on the top of the atmosphere is only determined by location and time (and to a lesser extend solar activity), the radiation that hits the earth's surface is influenced by the atmosphere. Even if there are no clouds radiation is scattered by the compounds in it. This means that a portion of the incoming radiation on each square meter of the earth’s surface comes from the direction of the sun, and a portion comes from all conceivable directions (Even light reflected from the ground back onto an absorber is sometimes accounted for in calculations). In the case of flat plate systems, the direction from which radiation originates is not important, the energy is absorbed anyway. But all radiation scattered by the atmosphere (diffuse radiation) that comes in at an angle greater than the acceptance angle of a concentrating technology cannot be utilized.

High concentration systems can only utilize direct normal radiation

This means that concentrating technologies are much more sensitive to weather conditions than are flat plate technologies and that the effect becomes worse with higher concentrating ratios. Flat plate technologies are merely influenced by the fact that some radiation is scattered back into space

High concentration systems are highly dependent on weather conditions by clouds but they are hardly affected by the angle of incoming radiation.

Insolation, Insulation, Reflectance & Heat Dissipation.

Unfortunately the problems with concentrating technologies do not stop there. In the case of thermal systems a high concentration ratio is required to achieve higher temperatures. These higher temperatures are achievable because the lower absorber area means that the heat dissipation from the absorber to the environment is limited. Flat plate technologies on the other hand have a large absorber area (the aperture area IS the absorber) and dissipate more of heat to the environment. The total heat-dissipation to the environment is apart from the absorber area, mainly influenced by the insulation and the temperature of the absorber, or to be precise the temperature differential between the heat transfer fluid (HTF) in the absorber and the ambient temperature.

Higher operating temperature cause lower efficiency of solar collectors.

At one point the temperature of the HTF becomes so high that all energy that is collected by the absorber is immediately released back to the environment. This temperature is known as the *stagnation temperature*. The stagnation temperature is a collector design characteristic that can often be found on factsheets of commercial products, it is independent of the system configuration.

Non-concentrating technology cannot achieve high temperatures due to total heat loss at the stagnation temperature.

Thermal collectors need to insulate the heat in the HTF from the environment. This is often achieved with one or more layers of glass. Another complementary possibility is the use of a vacuum to limit convection heat transfer. This principle is used in for example evacuated tubes collectors (ETC), or at the absorber tubes that are part of PTC's. The problem with insulation is that although heat from inside the collector must be isolated from the outside, radiation must still be able to get in. This poses difficulties as for example multiple sheets of glass each reflect a portion of the incoming radiation. There thus exists a trade-off: most technologies that effectively capture radiation due to low reflectance become less efficient at high temperature due to low insulation and vice-versa.

The available amount of radiation also plays an important role, not only for total yield but also for efficiency. This is illustrated in Figure 10. Note that the dependence of efficiency on interacting, often time dependent, factors such as insulation, reflectance, operating temperature and radiation, makes predicting or simulating actual performance quite complex!

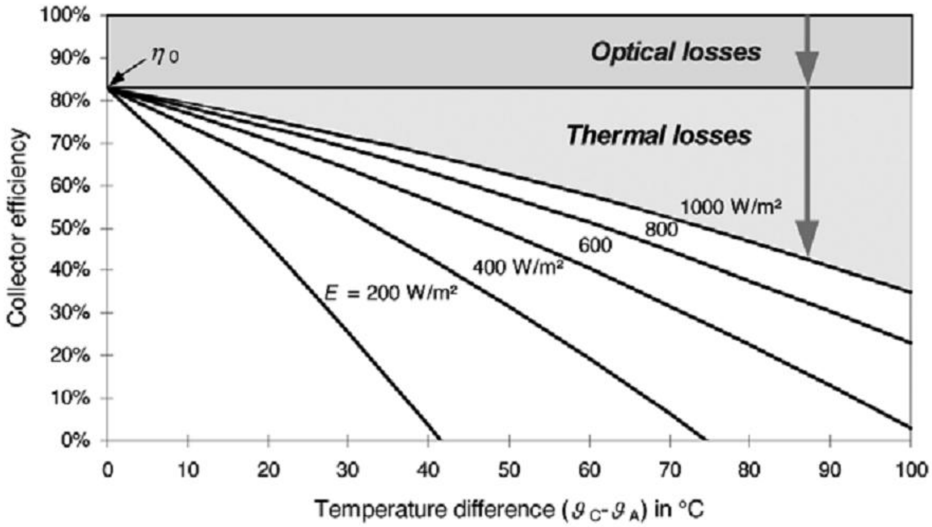


Figure 10, Collector energy losses as function of temperature and radiation level (Kalogirou 2004)

2.3 Energy Conversions, Storage & Efficiency

Natural Gas Displacement

The economic value of heat collection systems can be determined by the value of natural gas that is no longer needed in order to satisfy heat demand. If the heat could be converted into electricity (the price of which is higher than natural gas) the economic performance could be improved. The important question then becomes: how efficiently can a system convert solar irradiation into heat and then into electricity?

Heat Dissipation and the Carnot Efficiency

The first and second laws of thermodynamics cause a very important and unfortunate effect that is fundamental for understanding Solar Thermal Electricity Generation (STEG) combined heat and power (CHP) and solar assisted combined heat and power (SA-CHP).

Given only the first and second laws of thermodynamics, namely; the energy content of a closed system is constant and the total entropy of a closed system always increases (or is constant when there are no irreversibilities) one can easily derive the theoretical maximum efficiency of the conversion of heat into work. This theoretical maximum efficiency is known as the Carnot efficiency and depends only on the temperature difference between the cold and hot heat sinks. It is given by:

$$\eta_{carnot} = 1 - \frac{T_c}{T_h}$$

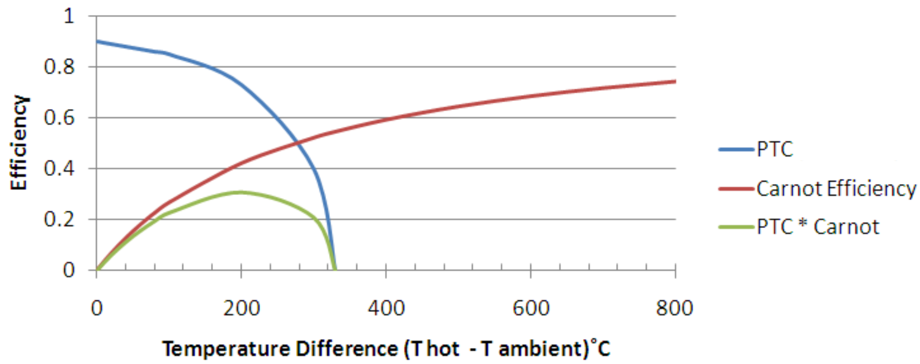


Figure 11, Efficiency of a Solar Assisted Carnot Engine (based on a fictitious PTC with a stagnation temperature of 330° C), as a function of Temperature Differential

Solar Thermal Electricity Generation

The Carnot efficiency explains why STEG systems often have both a cold and a heat storage system, the higher the temperature differential the higher the efficiency with which the conversion from heat into work can take place. The fact that lower temperature heat cannot be efficiently converted into electricity is the reason behind the usefulness of Combined Heat and Power systems. CHP systems do not attempt to convert all heat into electricity but instead produce 'waste' heat that is of sufficient temperature to be utilized in other ways. It is often more economical (in a broad sense) to utilize medium temperature heat in other processes than to try it to convert into electricity, however this does require that some process with a large heat demand is nearby (to limit transport losses).

High operating temperatures decrease the efficiency of the conversion from solar radiation to heat but increase the efficiency of converting that heat into electricity.

So what is so important about the Carnot efficiency when it comes to solar power investments? The point is that to increase the efficiency of an engine one needs to increase the operating temperature while solar collectors themselves become less efficient at higher operating temperatures! This is illustrated by Figure 11. The figure shows the fictitious performance of a PTC collector, the Carnot efficiency, and the maximum theoretical efficiency of the conversion of solar heat into work using this collector (PTC*Carnot).

The graph shows that the optimal operating temperature of this collector-Carnot engine combination is about 200 °Celsius and that the system has a theoretical maximum efficiency of about 30% In practice turbines operate at a fraction of the theoretical maximum efficiency and the connected generator (although highly efficient) also causes some losses, which together paints a grim picture.

On the other hand one should realize that although the pictures shows a low achievable efficiency for STEG systems, solar radiation by itself has no direct costs. If something has no costs then why is it important to use it efficiently? The problem is obviously that higher temperature systems are required to produce any worthwhile amount of electricity. This means that concentrating technologies are required with all the downsides described above and that the investment costs of these systems are often higher than for lower temperature systems.

Natural Gas Assisted Solar Power

In literature authors refer to STEGS (solar thermal electricity generation) mainly when talking specifically about the systems in California USA, and as such describe systems that do not use fossil fuels or biomass to co-fire. The plants are optimized to operate at relatively low temperatures and have relatively low investment costs[1], but at the same time are limited by the low maximum achievable Carnot efficiency. But one can imagine that another solution is possible: achieving higher temperatures with the help of fossil fuels, often natural gas. Hereby one can achieve higher temperatures and thereby higher efficiencies, at the costs of fuel consumption[2].

Heat Storage

The fact that heat is much easier and cheaper to store than electricity is a major benefit for solar thermal systems. For example the STEG systems in the USA described above include a storage system that allows for continuous operation of the turbine even during nighttime. At the same time, the storage system allows to boost production when electricity prices are high. Storage design in a solar energy system can have a considerable effect on economic feasibility (Duffie and Beckman 1980).

It is important to mention that heat storage for solar energy systems is only important or beneficial if the heat production of a collector field (plus process

[1] No expensive high temperature resistant materials are required

[2] The difference between a *'natural gas assisted solar plant'* and *'a solar assisted natural gas plant'* is only a matter of semantics, both produce electricity. CHP & SA-CHP on the other hand produce BOTH heat as well as electricity!

waste heat) can become larger than the heat demand of the host facility at any given point in time. If not, all heat can be used directly.

Solar Assisted Combined Heat and Power

In this case we consider a combined heat and power (CHP) plant. This facility should be designed so that waste heat is of sufficient temperature to be used in some other process. When calculating the efficiency of such a plant one must consider both the electricity and the heat it generates. Important is thus to establish if there is a heat demand on the location that is under consideration. Many industrial sites require large amounts of medium to high temperature heat. One could start by building a normal CHP plant, and later connect a solar field to preheat feed water, thereby creating a solar assisted combined heat and power plant (SA-CHP). However, it might be wise to adapt the design in advance so that the connection can made without difficulties.

Comparison with other renewable energy technologies

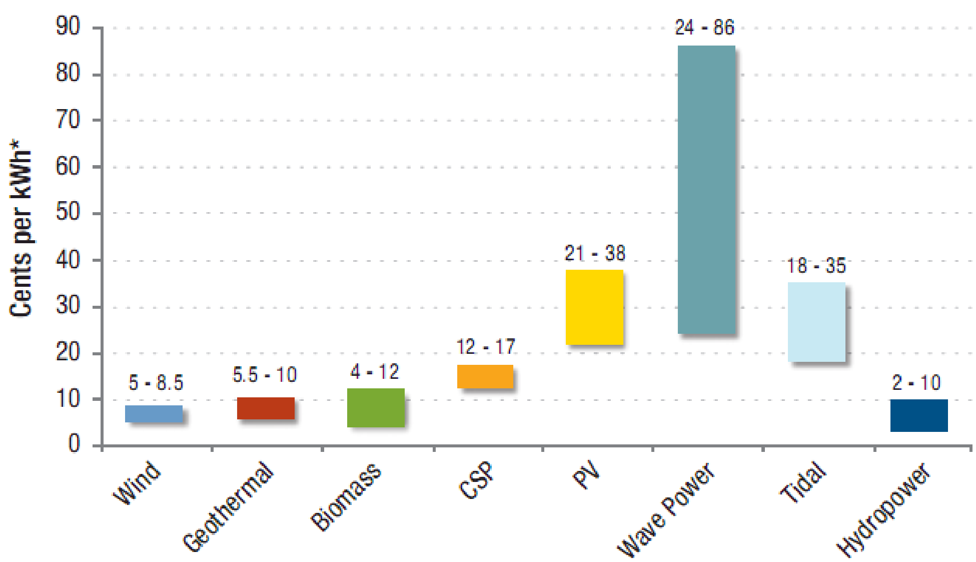


Figure 12, RET 2007 cost comparison. Average cost will vary according to fnancing used and the quality of the renewable energy resource available.(indirect Sources: Sandia National Laboratory, Idaho National Lab, Carbon Trust, Simmons Energy Monthly, U.S. DOE EERE, California Energy Commission, IEA, SolarBuzz LLC (U.S. Department of Energy 2008)

Although the performance of systems can greatly vary depending on the specific type and the circumstances Figure 12 illustrates that solar technologies are relatively expensive. On the other hand interpreting this figure can be difficult. For example, simply concluding that the application of CSP is cheaper than PV is only possible when one neglects that PV is very versatile and that most CSP systems that are operational, reside in extremely sunny areas. Although the source neglects to mention this, the costs are most likely calculated using a levelised electricity cost method, which is much more meaningful than direct investment costs. This figure does not include the value of systems that can provide heat but not electricity.

2.4 Chapter Summary

This chapter's intent is to provide the non- solar expert with the knowledge required to understand the basics of solar engineering and interpret the remainder of this report.

Important is that solar systems come in many forms and are composed of more than only the solar collectors. Mounting systems, inverters, auxiliary electronics, tracking and heat transfer systems are examples of other important components.

Also important is the fact that thermal collectors become less efficient at higher temperature (due to heat dissipation) whereas the generation of electricity becomes more efficient at higher temperatures.

Concentration of radiation before heat absorption can keep the heat dissipation area low. Thereby concentrating systems can achieve higher temperatures at reasonable efficiency. These systems however can only use direct normal radiation and require complex mechanisms to track the motion of the sun, this makes them sensitive to atmospheric conditions and relatively expensive respectively.

PART II : Establishing a Basis of Design

Chapter 3. Stakeholder Goals

This chapter is concerned with answering the following research question:

- *What are the objectives and constraints that follow from DSM's views and perceptions?*

The figure below shows how this question (and this chapter) relates to the meta-model and the design process. A similar figure will reappear at the start of most chapters to illustrate its position within the research.

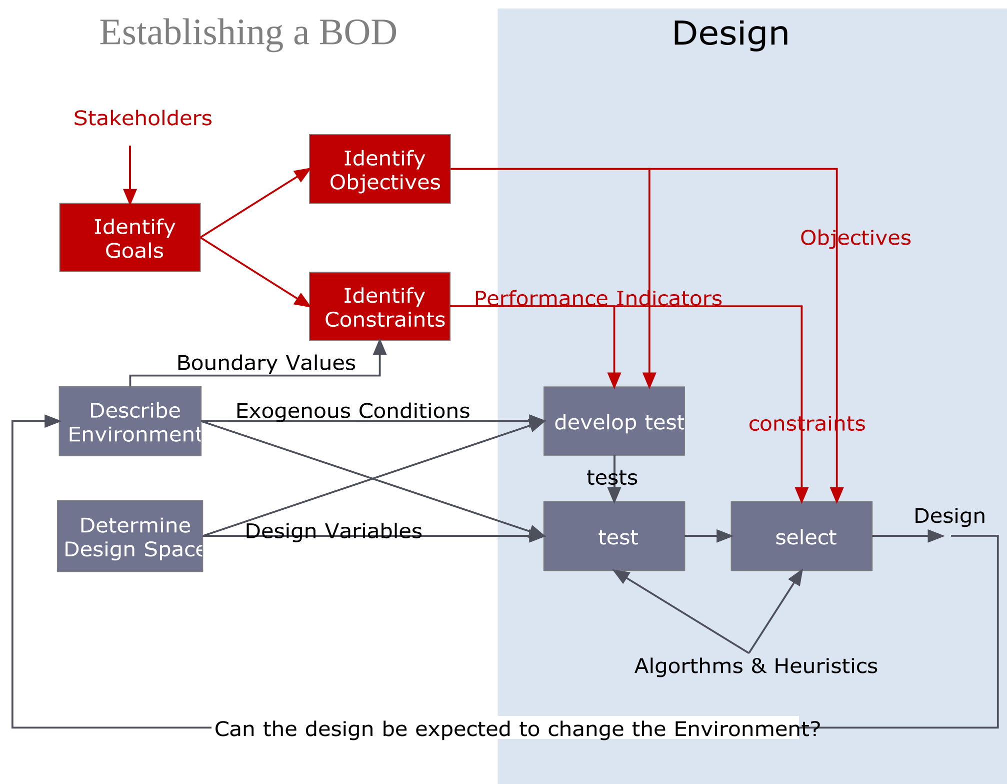


Figure 13, Chapter 3: relation to Meta Model

As explained in section 1.6, the terms goals, objectives and constraints have very specific meanings throughout this report. Objectives are “nice to haves”: things that the design sets out to achieve. Constraints are “need to haves”[1]: things that the design needs to fulfill to be acceptable. Goals are simply all objectives and constraints combined. This chapter summarizes the effort to

[1] The terms “objectives” and “constraints” do not imply a difference in importance!

discover, define and operationalise goals based on the views of the stakeholders. Operationalisation is the process of making goals measurable. For example, the goal of *improving environmental footprint* as used in the main research question is not directly measurable.

Key Performance Indicators (KPI's) will be formulated as means to measure performance. These should not be confused with Key Performance Drivers (KPD's); these are factors that determine the performance of solar alternatives and will be discussed in later chapters.

This chapter discusses goals and constraints and KPI's but lacks an overview. Instead, all tables are collected in Chapter 6: Basis of Design.

3.1 Process

The process of discovering and adjusting goals continued during the whole of the research. The researcher owes much gratitude to the many people at DSM that devoted time to the necessary discussions and interviews. Before continuing with the subject matter, this section describes this important process.

Questionnaire

Early in this research, a simple questionnaire was sent to various people at DSM. Ans Ligtenbarg and Kees de Glopper at DSM General, and Carlo Mariani at DSM Capua responded, see Appendix B[1]. Although, with the wisdom of hindsight, the questions seem vague and not very well defined, the results were quite valuable. Before the questionnaire returned, the researcher knew that solar energy was regarded a solution, but was unsure about the problem that it was intended to solve.

Different perspectives

The questionnaire illustrated that DSM General and DSM Capua look at solar energy from somewhat different perspectives[2]. DSM General mainly values the learning value of a solar energy pilot project. While DSM Capua shares this goal, it is more focused on the direct financial and ecological consequences. For example: both state a maximum payback period of about 5-7 years but DSM Capua graded this a relative importance of 10 out of 10 while DSM general graded a 5 and a 0 and added in a note: *"not so important for pilot project"*. The different perspectives are most likely related to the risks

[1] Permission was given by the respondents to present questionnaire results including names.

[2] It is assumed that Ligtenbarg & de Glopper represent the views of DSM General and Mariani represents the views of DSM Capua for the purpose of this research.

that both parties expect to bear. This led to the decision to regard them two different stakeholders during this research.

Presentation and discussions refined research

About five to seven presentations about the research progress were given during the research period. This was advised by people at DSM when the researcher, admittedly, failed to communicate pro-actively. These presentations, followed by discussions, proved excellent occasions to focus the research and discuss for example what key performance indicators are important at DSM. These discussions additionally often resulted in people offering help and information.

Sustainability forum

The researcher was also invited to visit the yearly DSM sustainability forum. This experience was extremely interesting (and fun). It clarified the context in which this solar energy research could be placed, and illustrated the devotion of DSM to sustainability. The forum seemed an important gathering within the decision making process, a presentation by (and lunch with) Professor Braungart, co-author of *Cradle to Cradle* was inspiring as well.

3.2 Defining Stakeholders

DSM Capua

DSM Capua is clearly the main stakeholder in this project. It is the party that can have the most benefit from a solar project but also bears most of the resulting risks. To be able to provide this stakeholder with the information it requires to make a balanced decision it is important to define appropriate key performance indicators.

DSM General

DSM General is a term used during this research to depict all of DSM's organization apart from the individual production locations. DSM General's goals with respect to pilot solar power are concerned with gaining knowledge, understanding and experience with solar technology as a possible means to achieve company goals, economic and ecologic and prepare for a future with very high fossil fuel prices.

Other stakeholders, such as the local municipality, were considered but not regarded so influential that their inclusion in analysis would result in other constraints and objectives[1].

[1] *During this research, a proposal to investigate a multi actor project, where different companies together invest in a central, large-scale power plant at a favorable location, was considered unrealistic under the current circumstances. If, in the future such a project is reconsidered, a very thorough stakeholder analysis is highly recommended.*

3.3 Objectives

Improving the environmental footprint (not reducing) was clearly regarded a major objective of any solar power investment. This objective is quite ambiguous but several interviews with people at DSM helped clarify it. First; reducing the carbon dioxide emissions resulting from the production process was regarded highly important. Assuming that the plant continues to produce the same amounts of product, the aim is thus to reduce the emission of carbon dioxide.

Environmental Footprint

Another (highly related) objective was to reduce fossil fuel consumption. Therefore, reduction of electricity and natural gas consumption were chosen as key performance indicators.

Fossil Fuel Consumption

Economic objectives included a short payback period (PBP) and high net present value (NPV). Reduction of fuel costs was regarded important by DSM Capua and so was limiting economic risk in the sense that the predictability of performance (of a solar energy system) should be high. This means that a form of risk assessment is necessary.

Economic Performance

Internal Rate of Return (IRR) was, on request, also considered as a KPI. However, although IRR is suitable for making a go/no-go investment decision, it is not very suitable for comparing mutually exclusive projects, which will be necessary during this study. For more information about the difficulties of IRR in this respect see (Kelleher and MacCormack 2004). Additionally the calculation of the IRR proved problematic in combination with Monte Carlo Simulations.

Internal Rate of Return problematic

The idea that solar power could be beneficial to DSM initiated this project. The purpose of a pilot project at Capua was not only to achieve economic and ecologic benefit directly but also to learn from the experience. Here discrepancy started to appear between DSM Capua and DSM General. Whereas people at DSM General highly valued learning effects, DSM Capua found direct benefits more important. This makes sense as the indirect value of learning would hardly be beneficial to DSM Capua. However because learning value is very hard to define and operationalise it is only discussed qualitatively.

Common objectives, different priorities

A reduction of variable costs (energy costs) was regarded highly important at Capua whereas DSM General found the economic performance of a pilot project less important. Likewise DSM Capua regarded limiting financial risk and a high predictability of energy system performance very important whereas DSM General found a higher risk level quite acceptable. Net Present Value and payback period were chosen as key performance indicators. To investigate risk and uncertainty the models need to be able to present expected values as well as a probability distribution or a confidence interval.

Learning Effects priority for DSM General, direct Effects priority for DSM Capua

NPV and PBP and their "spread" thus form the main economic performance indicators during this research. Additionally DSM (Corporate and Capua) made clear that the initial investment for a solar pilot project should not exceed 5 Million Euros. Investment costs are not a design parameter as the designer can only indirectly influence it and because it is subject to uncertainty. Therefore it is regarded a performance indicator (and model output) during this study.

"Environmental (or ecological) footprint", the term used in the main research question, can be considered a metaphor for the impact that activities have on the earth's ecosystems and resources. The term is very hard to define or clearly measure. However, discussions made clear that fossil fuel consumption reductions and especially carbon dioxide emission reductions (at a constant level of production), where regarded reliable and sufficient indicators for improving the environmental footprint.

3.4 Constraints

One major constraint that has been identified is that the initial investment in a pilot solar energy project by DSM at Capua should not exceed approximately 5M Euros. This has had consequences for some technologies that are only suitable for large scale application, such as central receiver systems.

The investigation of the facility (in chapter 5) also led to the constraint that the maximum amount of space that a solar system may occupy is about 60000 square meters. However given the costs of solar panels it is likely that the financial constraints of 5 million Euros will be the limiting factor.

Some respondents indicated that DSM is willing to loosen the conditions with respect to return on investment and payback time due to the experimental and sustainable character of the investment. Various respondents indicated a maximum payback time for a solar project of approximately 5 years, which is considerably longer than would normally be considered.

Although a longer than normal payback time is acceptable, respondents at DSM Capua found a high predictability of performance and investment costs much more important than colleagues at DSM General. Partly this can be explained by the fact that the risk will probably not be evenly distributed. Because predictability of performance this research will present simulation results as confidence intervals whenever possible. Because some technologies are more sensitive to exogenous factors than others, this might prove an important differentiating factor.

Requiring a high predictability of performance might be very wise from a totally different perspective: a solar project that eventually turns out to be performing much worse than expected, could severely damage the motivation to ever try again. A less-gain less-risk project might thus be favorable for developing a long term solar strategy.

Another constraint that followed from DSM's views was that the applied solar energy technology must be commercially available. Both DSM General as well as Capua had no interest in experimental or unproven technologies.

3.5 Chapter Summary

In accordance with the research question, this chapter discussed the objectives and constraints following from the two main stakeholders, DSM Capua and DSM General.

DSM Capua is mainly interested in directly reducing GHG emissions and reducing variable energy costs of the facility via a solar power investment. DSM General is more focused on the learning value of such a pilot project as a means to investigate the broader applicability of solar technology to achieve similar company goals.

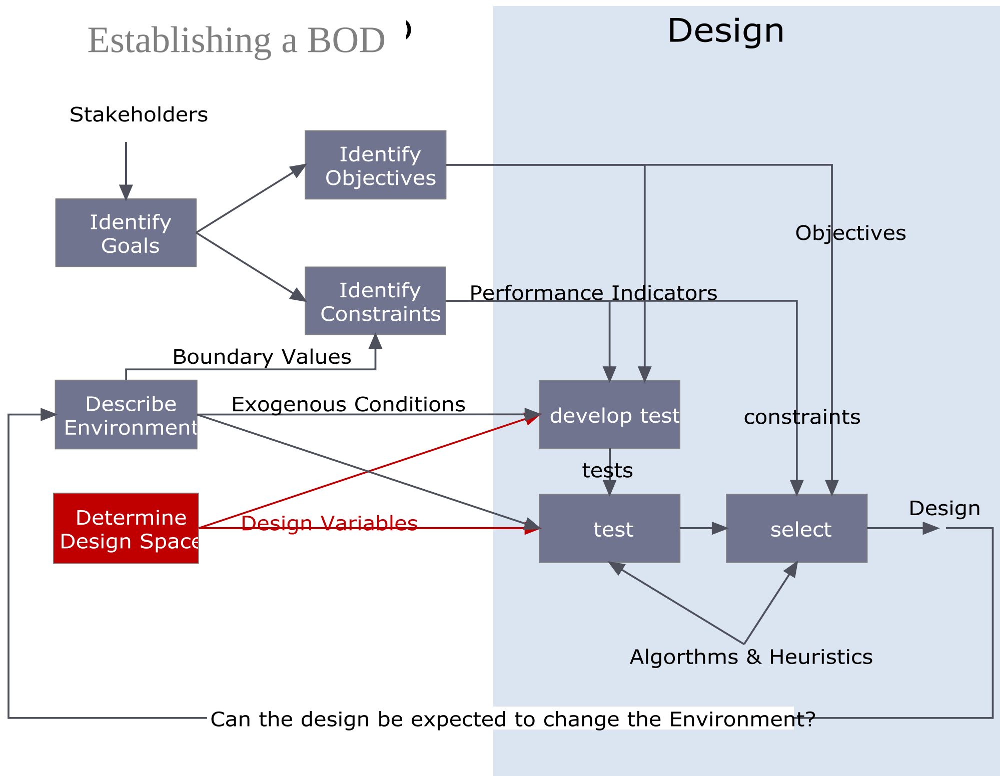
The complete answer to this question takes the form of a table of objectives and a table of constraints together with their respective figures of merit: KPI's that were chosen to measure performance.

These tables are not displayed in this chapter but instead collected in chapter 6: Basis of Design, together with tables displaying the design space and the exogenous conditions (that will result from the following chapters).

Chapter 4. Design Alternatives

This chapter is concerned with answering the following research question:

- *Which solar energy technologies are available for industrial application, and what are the key factors that determine their performance and applicability?*



Answering this question not only determines the technological design space but additionally identifies what exogenous factors determine the performance of the various technologies. These factors are named Key Performance Drivers (KPD), and are the factors within the operating environment that thus require further investigation to be able to model the conditions at Capua (this will be the purpose of the next chapter). This link between the design activities *determine design space* and *describe environment* was omitted from the above figure for the purpose of visual clarity.

4.1 Solar Technologies

As the introduction to solar engineering in chapter 2 made clear: solar energy systems are composed of various subsystems that can be combined in various ways. A literature study however showed that only a few system configurations and solar collector combinations make sense. Instead of treating solar collector technologies and system configurations separately, Table 2 presents an overview of the combinations (numbered) that will be considered during this research.

Table 2, Combinations of system configurations and collector-types. Numbers (#) refer to design alternatives.

<table>
<tr><th></th><th>Direct Electricity</th><th>Direct Thermal</th><th>Solar Thermal Electricity</th><th>Refrigeration</th><th>SA-CHP</th><th>CHP</th><th>Drying / Direct Chemical.</th></tr>
<tr><td>PV</td><td>1</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>C-PV</td><td>2</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Solar Ponds</td><td></td><td>3</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Flat Plates</td><td></td><td>4</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>PV/T Hybrid</td><td colspan="2">5</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Evacuated Tubes</td><td></td><td>6</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>L. Fresnel Heat</td><td></td><td>7</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Parabolic Trough</td><td></td><td>8</td><td>9</td><td>10</td><td rowspan="2">11</td><td></td><td></td></tr>
<tr><td>Natural Gas</td><td></td><td></td><td></td><td></td><td>12</td><td></td></tr>
<tr><td>Parabolic Dish</td><td>13</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Heliostat field</td><td></td><td></td><td>14</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Solar Furnace</td><td></td><td></td><td></td><td></td><td></td><td></td><td>15</td></tr>
</table>

Some combinations in table 2 are somewhat special, and therefore, the same technology (number) can be found multiple times in the table, this holds for:

- (5) PV/T-Hybrid, this technology requires a single collector type but a combination of two system configurations, one to collect heat, and one to collect electricity.
- (11) SA-CHP, this technology requires both a parabolic trough collector and natural gas firing. Natural gas firing is obviously not a solar collector type but nonetheless an alternative means to capture heat. It is included in the table to illustrate that STEG, contrary to SA-CHP, does not use natural gas firing and that CHP does not use a solar collector but solely natural gas.

This research also includes the research of Combined Heat and Power which is not a solar energy alternative but a conventional (non-renewable) energy technology. The inclusion of CHP in this research came about in a late state of the research when the investigation of Solar Assisted CHP led to the insight that CHP without solar assistance could achieve a much higher electric efficiency. In this case, the report thus does not fully reflect the iterative nature of the design process.

The table shows the 15 technologies that will be discussed. It illustrates that the Parabolic Trough collector technology is most versatile; it can be used in many system configurations. It is however important to note that the 15 alternatives should actually be regarded categories of technology. There are many forms of Photovoltaic technology for example. Each of fifteen technologies is briefly discussed in table 3.

Table 3, Solar Alternatives

Technology	Description
(1) Photovoltaics 	PV cells are mostly mounted on flat surfaces or flexible PV sheets for direct Elec. Generation are becoming increasingly popular on roofing. A multitude of technologies and manufacturing processes are possible. Options range from space-grade high efficiency collectors (of very high costs) to panels of low efficiency and relatively low investment costs .PV systems are sometimes combined with single axes tracking. Integration with alternating current systems and/or grid connection requires substantial investments in invertors and auxiliary electronics.

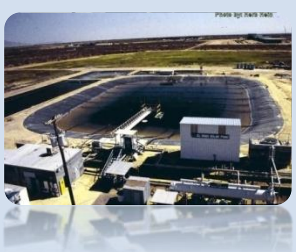
An important factor that distinguishes PV from thermal solar technologies is that, depending on the used materials, PV systems can only utilize a portion of the solar spectrum. Which is location depended due to the influence of the atmosphere.

A very thorough introduction to PV technology can be found at http://pvcdrom.pveducation.org/index.html (Honsberg and Bowden 2009)

(2) Concentrated Photovoltaics

Concentrating reflectors or lenses are used to focus radiation onto a small area of high intensity PV cells. The intent is to reduce PV cell area to achieve lower investment costs and material usage. Expensive PV cells are required but in lower quantities for the same electrical output, additional investments include reflectors and a tracking system. (The illustration shows a Linear Fresnel PV system.)

(3) Solar Ponds



High salt gradient water ponds that absorb (and store) heat due to disruption of natural heat convection. High temperature water layers in the pool are inhibited from rising to the surface (and dissipating heat there) by high salt concentrations. Heat thus trapped at the bottom of the pool is harvested by heat exchangers. The system is both a collector and a heat storage device. Temperatures up to 90 degrees centigrade are achievable.

(4) Flat Plate Collectors

Flat (non-tracking) collectors with circulating heat transfer fluid. The coated panels absorb incoming radiation. As the temperature of the heat-transfer fluid (often water with anti-corrosion and anti-freezing additives) increases, the efficiency of the system decreases because the large contact area between the absorber and outside air causes heat-loss.

(5) Heat/PV Hybrids

PV & Thermal Flat Plate integrated systems for combined heat and elec. generation. Higher efficiencies are achievable compared to non-hybrid systems due to cooling of the PV cells (which increases their performance) and simultaneous utilization of waste heat.

(6)Evacuated Tubes

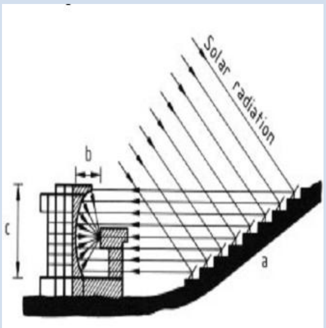
In order to reduce heat dissipation an absorber tube is placed in a second, evacuated and transparent tube. The construction is more expensive compared to flat plate collectors due to difficulties in the production process. However, the system achieves higher temperatures and efficiencies. In addition, because the absorbers are circular tubes, the angle of incidence does hardly affect the effective absorber area, which results in a relatively flat efficiency profile over the day. With direct flow systems, the heat transfer fluid flows through the inner tubes directly. Heat pipe systems are based on an evaporation cycle under vacuum within the inner tube, which transport heat to main transfer fluid at the top of the pipe.

The copper heat pipes within the evacuated tubes are very sensitive to impurities in the metal. Oxygen and other trace element form a bubble in the otherwise vacuum inner tube, and thereby create a considerable barrier for heat transfer. Heat pipes thus have a high risk of degradation over their lifetime, and quality control is ex-

	tremely important.
(7) Linear Fresnel 	Linear Fresnel reflectors are comparable to parabolic troughs, but instead of parabolic mirrors, the Fresnel reflectors are a collection of narrow flat mirrors (sometimes they can be slightly curved, stressing the material) that are positioned next to each other in a straight line. They can be manufactured more easily (and cheaper) than parabolic mirrors and are less likely to sustain wind damage. Solar tracking can be more complicated with this technology, and efficiency is generally lower compared to PT's.
(8) Parabolic Troughs for Heat 	PT's are a widely used CSP technology. Parabolic mirrors concentrate light onto a line absorber tube to produce heat. The collector system requires 2D tracking. Heat-transfer fluids preferably have high boiling temperatures and can be connected to a secondary steam generation cycle. Weaknesses include wind damage, mirrors becoming less reflective due to dust and corrosion, frost damage and sensitivity to vandalism. To increase maximum temperature (without pressure problems) several heat transfer fluids were developed. Direct steam generation is also possible but this usually results in higher investment costs. Additionally heat storage can become more difficult.
(9) PT's for Solar Thermal Electricity Generation	PT Collectors can also be combined with electricity generation. STEG in this research refers to systems that do not use auxiliary heating using fossil fuels
(10) Solar Refrigeration 	Medium to high temperature heat from various types of collectors (mainly Parabolic Troughs) can be used to power ad-or absorption cycles, to produce chilled water. Commercial available when used for air-conditioning, rare examples of cold storage in agriculture can be found as well. Because the systems do not require the conversion of heat into work, they can be highly efficient as long as the Delta T is not too large.

(11)SA-CHP	A Combined heat and power system simultaneously delivers electricity and heat. Hereby higher overall efficiencies can be achieved. Only Steam based CHP systems can be combined with solar thermal systems. PT collectors can preheat boiler water before the conversion into work, and electricity.
(12)CHP 	CHP systems for industrial application are often based on direct combustion engines, For example gas turbines. Such systems can, at the industrial scale, have higher electric efficiencies than steam based CHP. Direct combustions systems do not use a steam cycle and there is thus no water to preheat. Making integration with a solar thermal system impossible.
(13) Dish Sterling 	3D collectors with double axis solar tracking systems. Radiation is concentrated onto a very small area in the center of a curved mirror. The heat at this point drives an external combustion engine, known as a *Sterling Engine*. This engine operates with air that is heated and cooled in a closed system. The resulting expansion and contraction drives a piston that is connected to a small generator. These engines are known for their reliability and high efficiency. As each Dish has an intergraded generator, they need few auxiliary systems.
(14) Power Tower 	This large-scale technology involves many large flat mirrors with individual tracking systems that reflect light onto a central receiver tower. On the receiver tower stands a heat exchanger where molten salt is used as a transfer fluid to produce steam in secondary cycles. These, in turn, drive turbines and generators. The systems often include a heat storage facility.

(15) Solar Furnace



Solar furnaces use solar radiation (concentrated) to power chemical or drying processes directly. An example in France can be found at http://www.promes.cnrs.fr/

4.2 Literature Overview

The table below presents the fifteen alternative technologies that were considered during this research. It summarizes the results of a literature review that was conducted to gain insight in the technologies (a large part of Chapter 2 was also based on the insights gained during this literature research). The table presents what type of literature discusses what technologies and additionally indicates whether the source discusses; technical modeling, economic modeling, presents a comparison or overview of technology and if it specifically targets industrial application.

Source	Type*	Technology Overview/Comparison	Modeling Technical	Modeling Economic s	Targets Industrial Application	(1) Photovoltaics	(2) Concentrated Photovoltaics	(3) Solar Ponds	(4) Flat Plates Thermal	(5) Evacuated tubes	(6) Hybrids	(7) Linear Fresnel Heat	(8) Parabolic Troughs Heat	(9). Solar Thermal Elec. Generation	(10) Solar Refrigeration	(11) Solar Assisted-CHP	(12) CHP	(13) Dish Sterling	(14) Power Tower	(15) Solar Furnace
(Patel 1999)	B	O		O	O	X														
(Quaschning 2005)	B	O	O	O		X			X											
(Duffie and Beckman 1980)	B	O	O	O	O			X	X	X			X	X	X	X			X	
(Goswami, Reddy et al. 2007)	R	O	O	O	O				X	X			X	X	X				X	
(Pollerberg, Hamza et al. 2009)	A		O												X					
(Tierny 2007)	A	O	O		O								X		X					
(Riffat 2004)	A	O			O										X					
(Cameron, Blair et al. 2008)	C			O		X	X			X			X							
(Napolitano, Franchini et al. 2008)	C		O		O								X		X	X	X			
(Kalogirou 2004)	A	O	O	O	O				X	X			X		X				X	X
(Luther, Nast et al. 2000) Ullman Encyclopedia	R	O	O	O	O	X			X			X	X					X		X
(Kulkarni, B. et al. 2008)	A		O		O				X				X							
(Kalogirou and Y. 2007)	A		O								X									
(Huang, Lin et al. 2001)	A	O	O	O							X									
(Kalogirou 2002)	A		O		O								X							
(Ucar and Inalli 2008)	A		O	O					X	X										

CONTINUED **Source**	Type*	Technology Overview/Comparison	Modeling Technical	Modeling Economic s	Targets Industrial Application	(1) Photovoltaics	(2) Concentrated Photovoltaics	(3) Solar Ponds	(4) Flat Plates Thermal	(5) Evacuated tubes	(6) Hybrids	(7) Linear Fresnel Heat	(8) Parabolic Troughs Heat	(9). Solar Thermal Elec. Generation	(10) Solar Refrigeration	(11) Solar Assisted-CHP	(12) CHP	(13) Dish Sterling	(14) Power Tower	(15) Solar Furnace
(Palumbo, Keunecke et al. 2004)	A	O			O															X
(Niemann, Kreuzburg et al. 1997)	A		O		O				X						X					
(Tamme, Bauer et al. 2008)	A		O					(Storage)					X							
(Dieng and Wang 2001)	A	O			O				(Literature Review)						X					
(Omer 2008)	A	O			O												X			
(Hang, Jun et al. 2008)	A	O		O									X	X				X	X	

***Type B = Book, A = Article, C = Conference, R = Reference work / Encyclopedia**

4.3 Future Technology Development

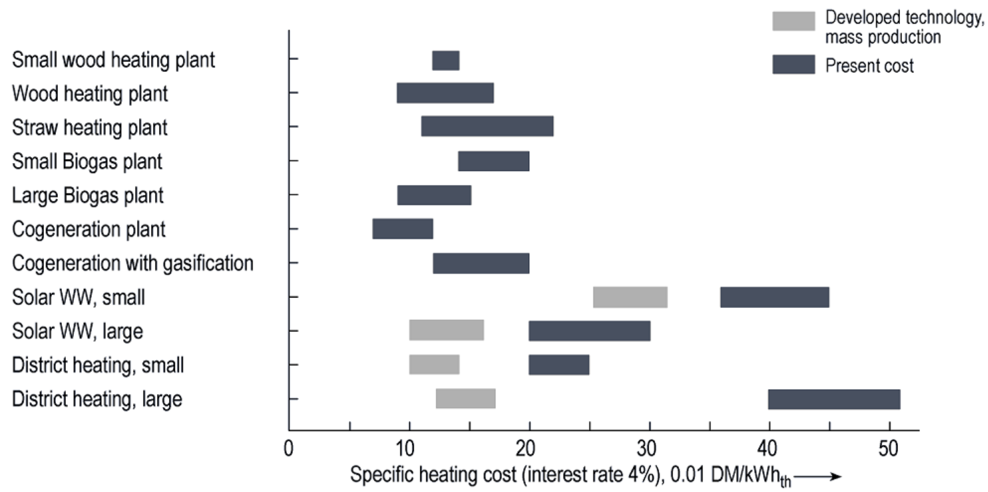


Figure 14, Cost reduction expectations from mass production (Luther, Nast et al. 2000)

Figure 15 illustrates that mass production is expected to lower the costs of solar alternatives. Nonetheless, these researchers expect that the application of small scale (non utility) remains relatively expensive when compared to cogeneration.

4.4 Design Space

Variable	Description	Considered Range
Technology Type	Industrial Solar Power Technologies, and Combined Heat and Power.	(0) Business as usual (1) Photovoltaics (2) Concentrated Photovoltaics (3) Solar Ponds (4) Flat Plates (5) Evacuated tubes (6) Hybrids (7) Linear Fresnel Heat (8) Parabolic Troughs Heat (9) Solar Thermal Elec. Generation (10) Solar Refrigeration (11)Solar Assisted-CHP (12)CHP (13) Dish Sterling (14) Power Tower (15) Solar Furnace
Scale	Size of the solar energy system measured by the land area it occupies expressed as a % of the available land area (65000 m^2)	0-100%
Capacity (CHP ONLY)	Size of CHP. Here CHP scale or capacity is defined as the maximum energy consumption of a	3MW <> 20 MW

	CHP plant. Alternatively It can be calculated by adding the electric output, the heat output and (thermal) losses.	(or 0 MW)
Electricity ratio (CHP ONLY)	Sometimes referred to as heat-ratio or electric efficiency. It is maximum ratio of electricity output divided by heat output.	0-1 but limited by available technologies (gas turbine, steam turbine, gas engine)

4.5 Identification of Key Performance Drivers

From the literature survey fifteen technologies were identified ranging from simple flat plates to advances central receiver systems. Identifying which variables are important for the performance of solar energy systems in general also clarified what factors need to be investigated at DSM Capua. These factors were named key performance drivers).

The literature research showed that key performance drivers differ between technologies. For example the economic performance of heat systems depend on natural-gas prices but this is not the case for PV systems. Table 4 presents what KPD's are expected to influence the performance of which technologies and whether it influences economic or ecological performance (or both). The KPD's are presented in a random order.

Table 4, KPD's and Effects

Key Performance Driver	Effect on economics?	Effect on Env. Footprint?	(1) Photovoltaics	(2) Concentrated PV	(3) Solar Ponds	(4) Flat Plates	(5) Evacuated tubes	(6) Hybrids	(7) Linear Fresnel Heat	(8) Parabolic Troughs Heat	(9) STEG	(10) Solar Refrigeration	(11) Solar Assisted-CHP	(12) CHP	(13) Dish Sterling	(14) Power Tower	(15) Solar Furnace
1 Electricity Price	o		x	x				x			x	x	x	x	x	x	x
2 Natural Gas Price	o				x	x	x	x	x	x		x	x	x			x
3 Global Radiation	o	o	x		x	x	x	x									
4 Direct Beam Radiation	o	o	x	x	x	x	x	x	x	x	x	x	x		x	x	x
5 Operating Temperature	o	o			x	x	x	x	x	x	x	x	x	x		x	x
6 Eff. of local elect .grid		o	x	x							x	x	x	x	x	x	
7 Heat demand pattern	o	o			x	x	x	x	x	x	x	x	x	x	x		x
8 Electricity demand pattern	o	o	x	x				x			x	x		x	x	x	
9 Direct subsidies	o		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
10 Feedback tariff subsidies	o		x	x							x	x	x		x	x	
11 Extreme Weather	o	o	x	x	x	x	x	x	x	x	x	x	x	x		x	x

Electricity Price & Natural Gas Price (KPD1&2)

An industrial facility as a whole does not benefit from high energy prices as long as it is a net importer. However, high local electricity and NG prices positively influence the economic performance of the solar systems because their income is calculated as the value of the amount of fuel that is no longer required. The economic performance of systems that produce (or consume) both electricity and heat are dependent on both NG and Electricity prices (TECH 6,10,11,12,15). Uncertainty about the development of energy prices has an important effect on the risk that is involved with the solar energy investment.

The electricity price also determines the income generated when surpluses are exported to the grid.

It is important to note that higher prices do not always influence the solar technologies in a positive way. For example CHP that requires the consumption of Natural Gas decreases its economic performance when NG prices increase. Table 4 shows only which KPD influences what technologies, it assumes no direction.

Global & Direct Beam radiation (KPD3&4)

Concentrating technologies can only utilize direct beam radiation (KPD4). Flat plate technologies can use both global (KPD 3) as well as direct beam radiation. These weather conditions influence the amount of energy that a solar technology can produce and thus influence both economic as well as environmental performance.

Operating Temperature (KPD5)

The efficiency of solar heat collectors depends on their operating temperature (KPD 5), because higher operating temperatures cause larger heat losses. The minimum temperature at which the solar system is required to operate depends on the process it is supposed to power. Technologies that cannot achieve this temperature are quite useless. The temperature of the heat demand of the facility at Capua is thus a very important factor that influences the applicability of solar technologies.

Efficiency of local electricity Grid (KPD6)

Countries that have an inefficient national electricity production have higher CO_2 emissions and higher fossil fuel consumption per MWH of electricity produced. The more environmental damage importing electricity does, the more valuable preventing electricity import becomes. Therefore the efficiency of the grid from which electricity is imported, determines the value of the solar energy systems that lowers this import (compared to business as usual).

Heat and electricity demand patterns (KPD7&8)

The volume and variation of local demand for both electricity and heat can be very important for the performance of solar energy systems. If the energy produced by the solar system cannot be utilized by the facility (or exported), it does not generate value.

Direct and Feedback subsidies (KPD9&10)

Local regulatory regimes with respect to subsidies can have an important effect on the economic performance of solar energy systems. Direct subsidies are hereby defined as those that reduce the direct investment costs of a solar facility. Feedback subsidies are those subsidies that relate to the actual power output of a solar system. Many countries have various forms of feedback subsidies in place for electricity generation, but not for heat generation.

Extreme Weather (KPD11)

Frequent high wind speeds (above 25 meter/second) and freezing temperatures can cause damage to some solar systems or require extra investments such as auxiliary heating (or another heat transfer fluid) to prevent damage. Although the Table 4 does not show it; extreme wind speeds influence all solar technologies except solar ponds but freezing mainly causes harm to heat systems because expansion of the Heat Transfer Fluid (HTF) causes damage to tubing.

4.6 Chapter Summary

In accordance with the second research question, this chapter identified and investigated different solar technologies (15) via a literature research. In addition a list of key performance drivers was identified, so that the researcher can focus on the most important factors when investigating the local conditions at Capua.

The first part of the answer to this question took the form of a list of solar technologies that together with variables such as scale makes up the design space. All overviews of the analysis results, including the design space, can be found in Chapter 6: Basis of Design.

In addition a total of 11 Key Performance Drivers (KPD) were identified including the temperature of heat demand (of the host facility). An important insight from the literature research was that solar thermal systems should be operated at low temperatures when possible to reduce heat dissipation. High temperature heat demand however requires higher operating temperatures, which in turn requires more advanced and more expensive technologies.

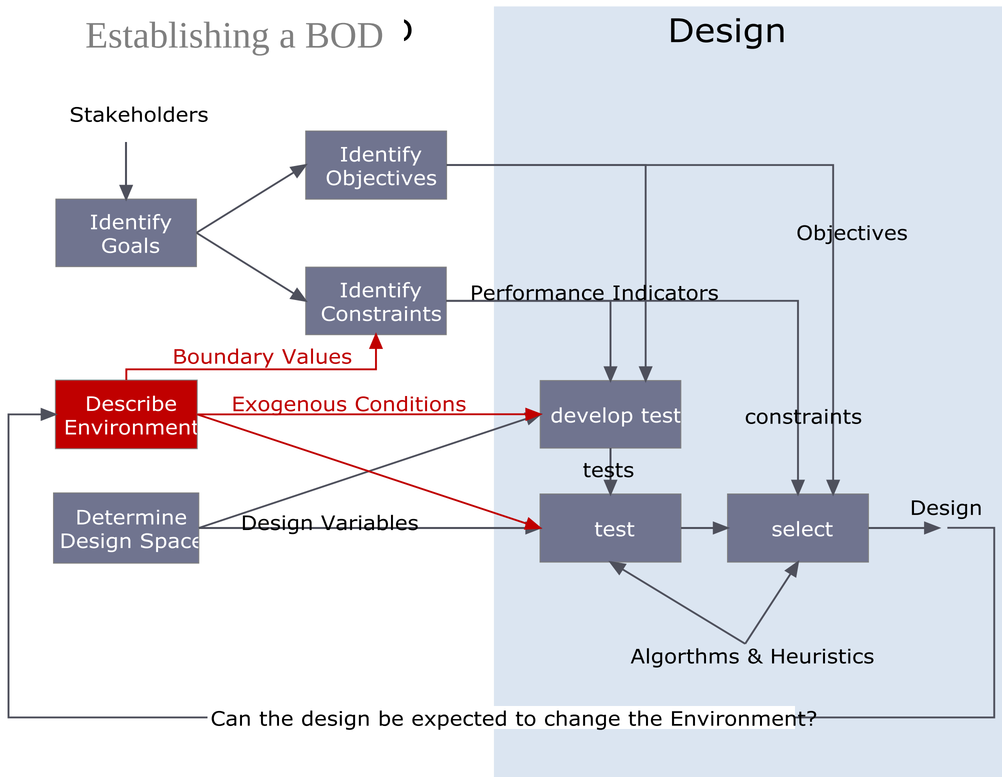
Advanced solar technologies often achieve high temperature by concentrating radiation before absorbing its energy. This keeps the absorber area small and the heat dissipation low. Unfortunately concentrating light can only be successful when the radiation is not scattered by the atmosphere. This makes the availability of direct normal solar radiation an important KPD for concentrating technologies whereas global radiation is more important for flat plate technologies. This illustrates that different technologies are sensitive to different key performance drivers. In addition, a distinction was made between KPD's that influence the economic performance and those that influence ecological performance (or both).

The Key Performance Drivers (KPD) are further investigated in the next chapter and this will result in a table representing the status (and assumptions about the future development) of these factors.

Chapter 5. Exogenous Conditions

This chapter is concerned with answering the third research question:

- *What are the relevant conditions for solar energy at DSM Capua?*



The identification and investigation of the design alternatives in literature also resulted in the identification of *key performance drivers* (in Chapter 4). These are considered the main factors that are expected to determine the performance of the various technologies at a specific location. These factors are outside of the control of the designer and therefore considered as exogenous conditions. This chapter summarizes the results of the investigation of the status, and assumptions about the future development, of these Key Performance Drivers.

Many of these profiles were used as input for a simulation model that predicted the performance of the various technologies under specific circumstances as will be discussed chapter 8.

KPD's are not the only relevant conditions for solar energy. The constraints that follow from the (physical) situation at Capua are relevant to solar power as well (for example available land area).

5.1 System Boundary

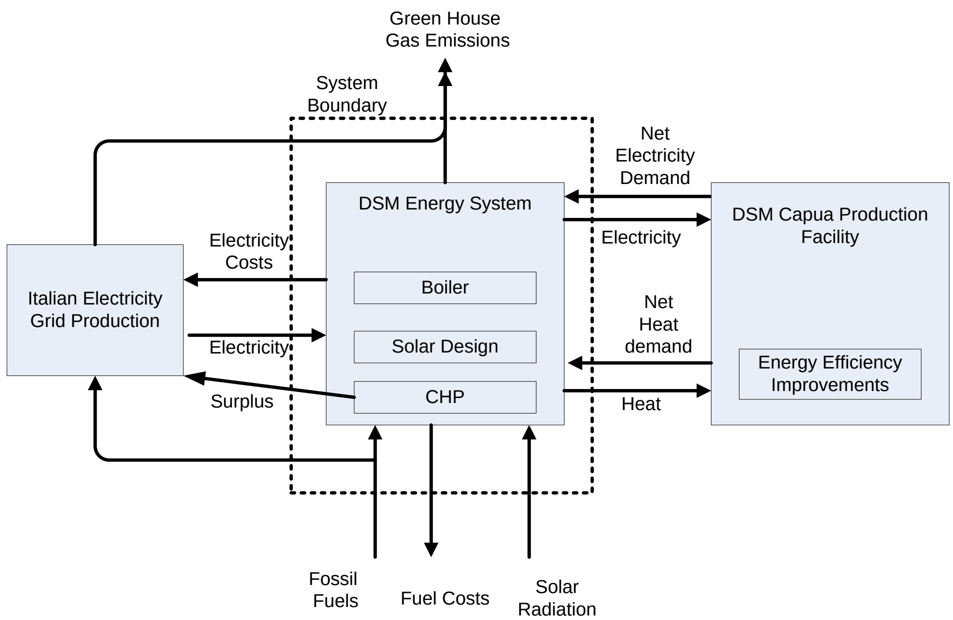
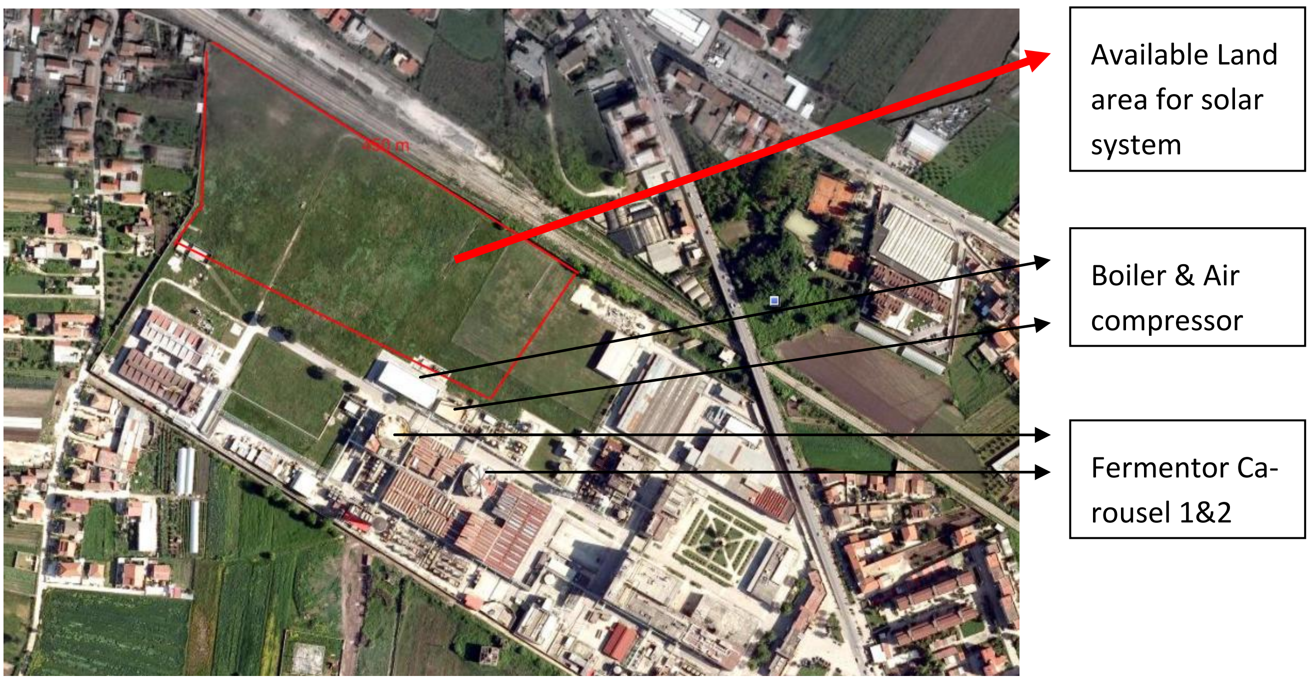


Figure 15, System Boundary

Figure 15 gives a graphical representation of the system boundary. It for example shows that the characteristics of the Italian electricity grid are considered exogenous (efficiency, prices) variables but that the green house gas emissions that relate to electricity import will be included in the calculations. The same holds for total fossil fuel consumption. A consequence of this is that onsite production of electricity can reduce total carbon dioxide emissions if it is more efficient than importing, even though the facility itself is increasing its local emissions. The idea is to evaluate the environmental impact that is a result of the production at DSM Capua, instead of merely the impact at the production location. The figure also shows that the production facility itself is considered outside the system boundary. This means that net heat and electricity demand are considered exogenous conditions that the designer has no influence over. This means that future variations in production rate and therefore net demand can be a risk for the solar investment. For example: *energy efficiency improvement* is obviously a positive thing for the facility as a whole, but can lower the performance of an energy system investment when there is a chance of overcapacity.

5.2 Introduction to the DSM Capua Production facility

Twenty-eight fermentation reactors, grouped in two carousels, stand at the heart of DSM Capua's production system. Each reactor, or 'fermentor' as they are called throughout the industry, can be used to host a batch process where a specially prepared feedstock is converted by a micro-organism into some product. One can combine various organisms and feedstocks to produce different products.



This sounds relatively simple, but there are two main complications. The first is that the microorganisms are highly engineered and must be held under very specific conditions to stimulate them to produce a particular product. The second major problem is that of contamination. A few engineered microorganisms must be multiplied into billions and feedstock must be prepared so that no other, unwanted, microorganism can enter the process and disrupt production. Unfortunately, the conditions that are necessary to multiply the microorganism are also favorable to other organisms and keeping them out of every process-step is not an easy task.

Other DSM facilities engineer the microorganism and transport them to production sites such as DSM Capua. Feedstock, that is sterilized using steam, is fed to a small vial of the organism (in a laboratory) until they multiply to a few kilograms. This is subsequently fed into a seed reactor. Each seed reactor connects to one fermentor and both are sterilized using 150˚C steam between each batch. Once the microorganism multiplied into a sufficient volume, it is transported from the seed-vessel to a fermentor (again via sterilized pipelines), another feedstock is added and the organism starts to convert that feedstock into the desired product.

The fermentation reaction is often exothermic and requires continuous stirring and cooling. This cooling is provided by chilled water that enters heat exchangers surrounding the reactor at approximately 10˚ C and returns to the chillers at around 20˚C. Additionally compressed air is transferred trough the fermentor unless the reactor is anaerobic.

Once the process is complete, the fermentor contains a mixture of feedstock, water, waste, product and the microorganisms. This mixture is then separated in a downstream processing facility. This facility requires both heat and cold. Heat is delivered by steam that originates from two natural gas fired boilers. Cold is delivered as 0˚C brine (a mixture of water and anti- freezing additives) that is delivered by a separate set of electricity-powered chillers and a circulation system.

On the DSM Capua site there is a patch of currently unused land of approximately 65000m^2. This is regarded the maximum land area that is available at Capua for implementation of a solar design.

A schematic was build in order to understand the industrial process at DSM Capua from an energy perspective and investigate the integration possibilities of solar power. The schematic (Figure 16) is a highly simplified representation of reality and was created with the help of various employees at DSM Capua.

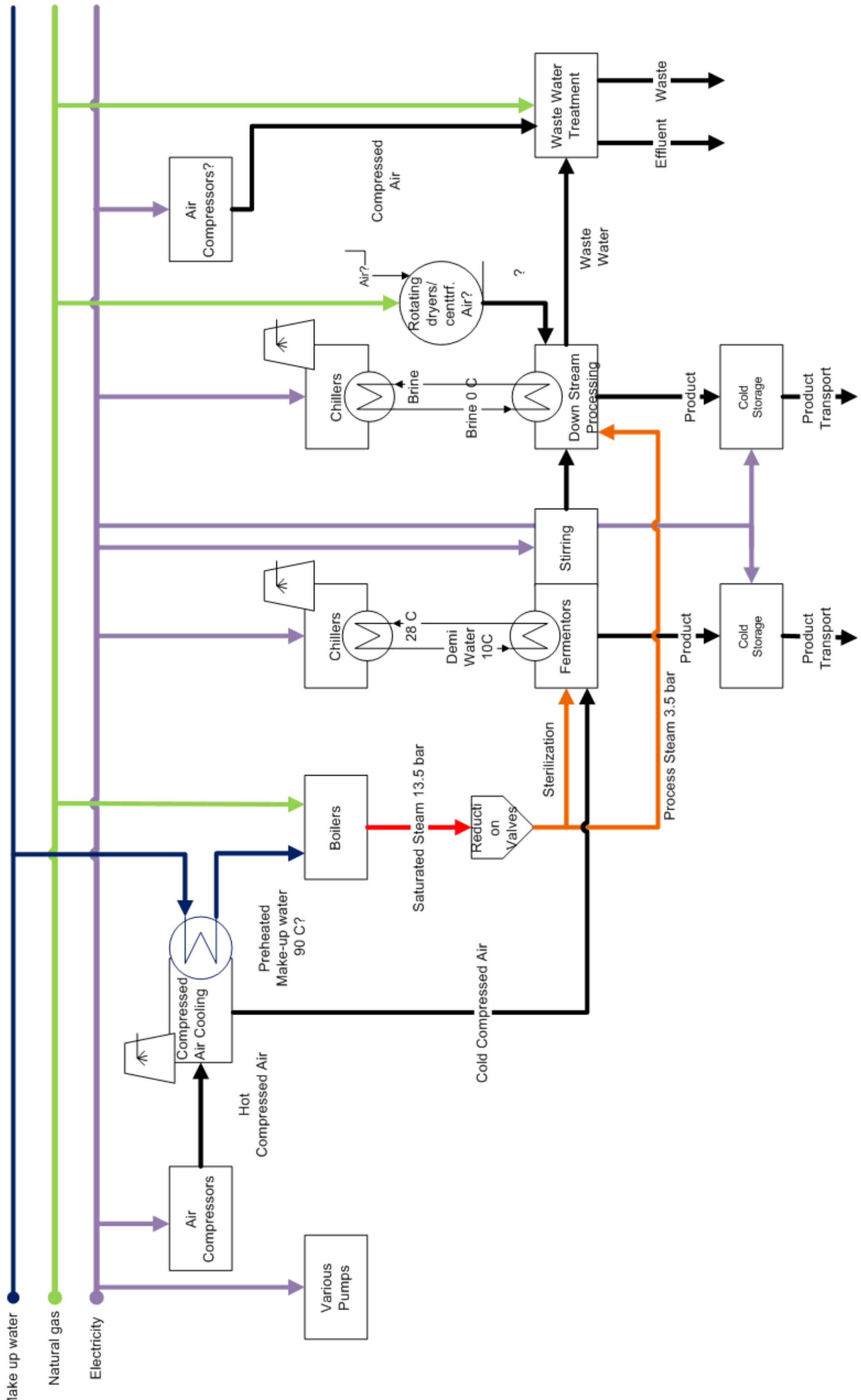


Figure 16, Overview of Industrial process at DSM Capua from energy perspective.

Saturated steam is produced in two natural gas fired boilers at 13.5 Bar, and then led trough reduction valves to produce the 3.5 bar steam that is required for sterilization and downstream processing. Higher-pressure steam was used in the past for operations that are no longer (or only very rarely) required.

The first concrete recommendation of this report must thus be to investigate the possibility to generate lower-pressure steam without risking contamination and thereby reduce natural gas consumption. This investigation needs to include analysis of FDA and internal regulations. It will require some time and investment but a pressure reduction from 13.5 to for example 5 bars can reduce the minimum operating temperature of the boilers and can thereby reduce the natural gas consumption of the facility.

Preheating Boiler water not applicable due to waste heat recovery from air-compressors

Because the steam that is used for sterilization is not recoverable (due to contamination risks plus some other factors), and steam that is used for product separation ends up in wastewater, there is no steam or water return to the boiler. Alternatively, make-up water is fed into the system after demineralization and then pre-heated using heat from the electric air compressors. As the volume of make-up water is relatively small and the air- compressors large, the water can be heated up to 90˚C and still small cooling towers are necessary to get rid of excess heat. This has important consequences as preheating boiler water via solar energy is thus not applicable. Heat provided by a solar system must thus be well above 90°C to be useful at the DSM industrial site.

5.3 Energy Demand

Natural gas is used for three purposes; steam production in the two main boilers, waste water treatment, and an air drying system. Figure 18 shows a steady consumption pattern in 2007-2008, with moderate seasonal variance. The two major drops in consumption were due to scheduled maintenance. Employees at DSM indicated that such a maintenance period occurs every year and that scheduling it during winter (when solar output is lower) is unlikely due to the Italian holiday schedules. Additionally a linear regression analysis shows a slow decline of average consumption over the last two years which is caused by a decrease in overall factory output.

Figure 17 shows the electricity consumption over the past two years. A similar pattern is found here. The linear regression model shows a somewhat faster decline in consumption during the last two years (compared to NG) which can partly be explained by the installation of more efficient electric motors.

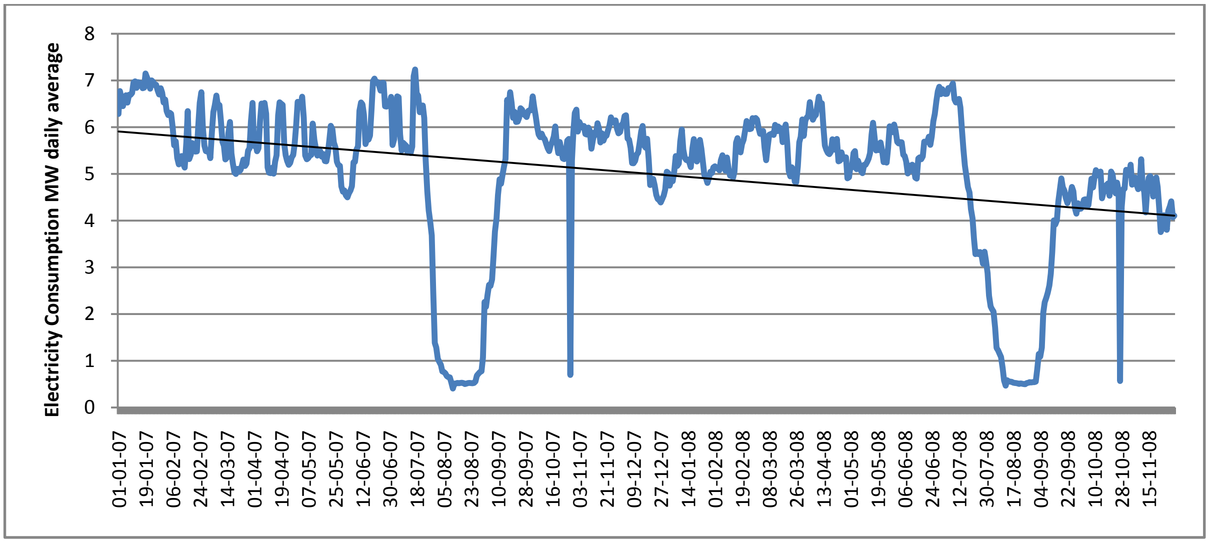


Figure 17, DSM Capua Electricity Consumption

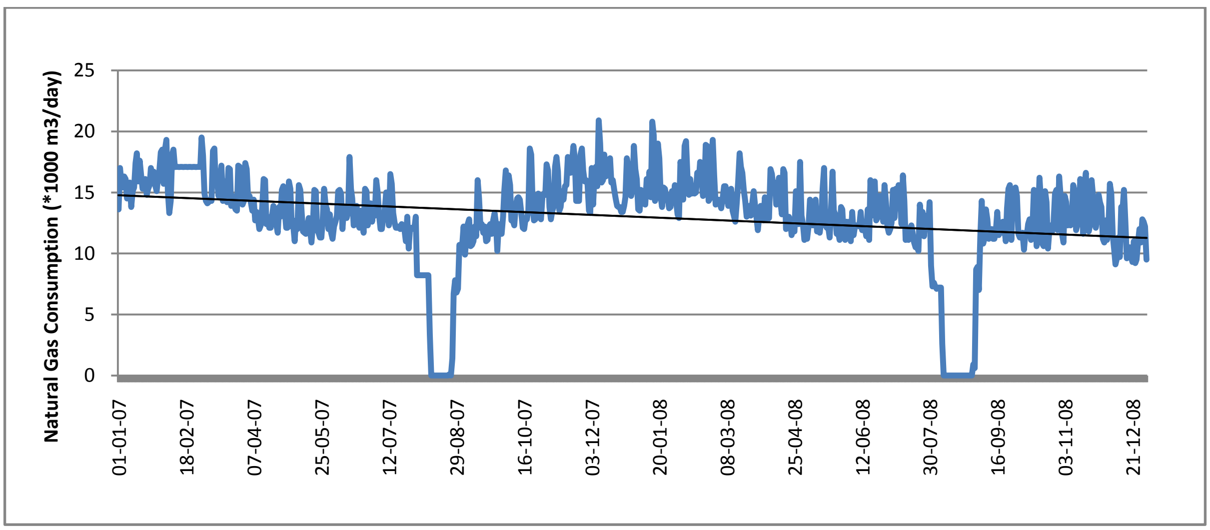


Figure 18, DSM Capua Natural Gas Consumption.

At least two power failures can be identified around 22-10-07 and 03-11-08. Electricity failures can easily result in the loss of a full batch of high value product. Increasing security of supply can be an important factor.

For the remainder of this report the researcher assumes that the future energy demand of the facility can be accurately modeled by looping the formerly discussed dataset. This approach was chosen over using the linear regression results because looping means that the scheduled maintenance periods are also taken into account.

These periods of low demand coincide with the summer periods where solar production can be expected to be high. This will most likely benefit (relatively) electricity producing systems that can export their surplus at the costs of systems that deliver a lot of heat when there is no demand.

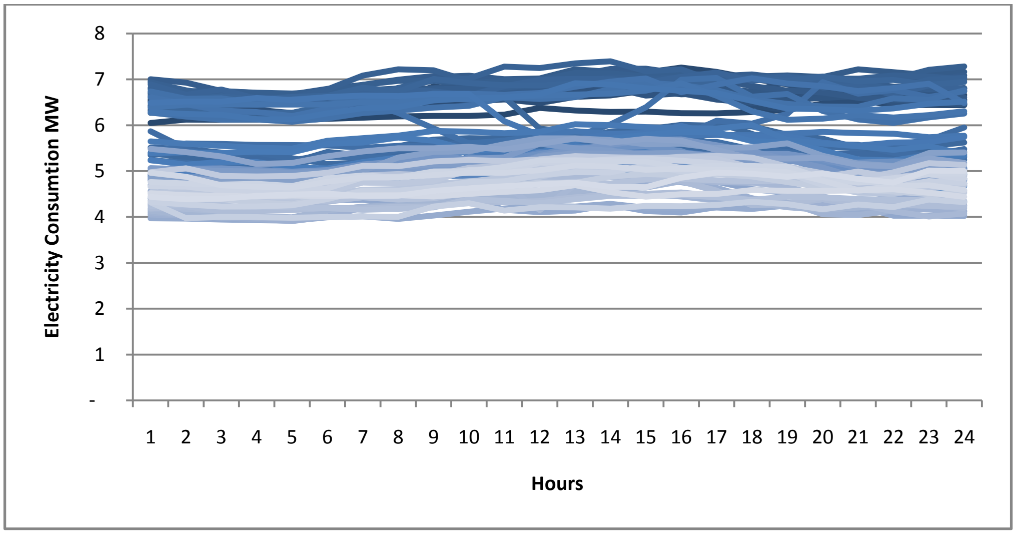


Figure 19, Random Selection of Daily Consumption Profiles

The daily electricity profile was also analyzed. The production of solar electricity varies greatly over the day (assuming there is no storage), and comparing it with the daily consumption pattern might prove important. If there occur large variations during a day, these must be accounted for.

Fortunately, the graph shows that the daily profiles are quite flat, variations of more than a MW within the course of a day are uncommon. The graph is created by selecting random days from the total dataset.

5.4 Integrating Solar Technology at DSM Capua

The method of integrating the solar technology with the industrial facility is, during this research, implied by the technology itself. If many substantially different possibilities exist, the design space becomes larger.

This research assumes that:

- Thermal systems are integrated to preheat the boiler via a secondary cycle and heat exchanger.
- Direct electricity systems are assumed to be fully grid connected (thus Alternating Current).
- Hybrid systems are assumed to integrate with both the above methods.
- Refrigeration systems abate the consumption of the electric chillers when possible, but do not replace them.

- CHP systems are assumed to be fully grid connected.
- It was concluded in a later stage that the solar furnace technology could not be integrated with the current production system and was thus excluded from further analysis.

5.5 Markets, Prices and Subsidies

Electricity and Natural Gas in Italy

Since 1980, energy usage relative to GDP (gross domestic product) has decreased 15% in Italy, indicating a trend of doing more with less. However in the same period the consumption of electricity increased more than 20%. This Indicates that more processes in the economy depend on electricity. The Italian energy authority *"Autorità per l'energia elettrica e il gas"* (AAEG) furthermore reports that domestic production accounted for about 86% while the rest was covered by imports. The limited interconnecting infrastructure of Italy and surrounding countries has caused a relatively low import capacity. In addition, regional management of electricity grids has caused a low transport capacity between different provinces. System stability often requires excess production capacity even at peak demand, and limited transport capacity makes that each region needs to provide for this itself. Excess capacity is rarely used by definition and therefore expensive, which could be part of the explanation why Italy's electricity prices are relatively high.

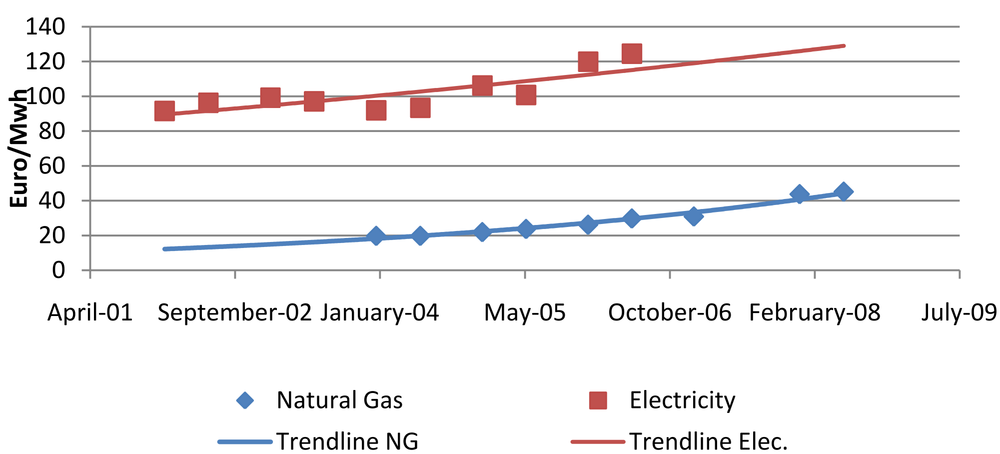


Figure 20, Development of Energy Prices for Industry, based on EuroStat data, price data from 2007 onwards was calculated by a renewed methodology, unfortunately many data points missing, exponential trend lines

Italy's electricity prices, both for residential and industrial use, are among the highest in Europe. Depending on the rate of consumption industrial consumers pay between 15,04 c€ and 7,20 c€ per KWh in 2007, excluding tax . With a yearly consumption of approximately 43.000 MWh by the plant of DSM Capua, the AEEG estimates an appropriate final electricity price of 7.2 c€/KWh (AEEG 2007; AEEG 2008) (see appendix K). Adding up to a yearly electricity bill of 3.3 Million Euro's. This is considerably less than the 5M Euro DSM Capua is currently paying at a yearly indexed price of about 11 c€/KWh.

It might be worthwhile to investigate what is causing this gap between the AEEG calculations and the prices DSM Capua is currently paying, regional prices and limited transport capacity could be an important factor, and improvement might not be possible at this location. This falls outside the scope of this research and the current 11 c€/KWh is used as a starting point for calculations.

Environment markets

In Italy, there seem to be four regulations that are potentially relevant for solar power at DSM Capua. First, a subsidy scheme called the "Conto Energia" that will be discussed in the next section, the European Union Emission Trading Scheme (EU ETS) and two domestic environment markets (both controlled by the GSE that is part of the Italian energy authority AEEG): the CIP6 system and the Green Certificates (GC) system. Producers that benefit from the incentives provided for under CIP6 cannot obtain GC (Puopolo and Croce 2001). The incentives are thus mutually exclusive.

EU-ETS: Cap and Trade

The European Union trading scheme (EU -ETS) was found not to be applicable because DSM Capua does not carry out any of the activities listed in the regulation (Energy sector, iron and steel production and processing, the mineral industry and the wood pulp, paper and board industry) (Directive 2003/87/EC of the European Parliament, annex 1). Even if it did, the current limit for applicability is a minimum of 20MW heat production, which is far above the current situation at DSM Capua. As a reference value, it is useful to note that currently (December 2009) emission permits are traded for approximately 14 Euro/tCO_2.

CIP6: Market Price Plus

CIP6 is an incentive mechanism that grants the producers of electricity from renewable energy sources a bonus (AEEG 2007). They can sell their electricity at a price that is somewhat higher than the market price. The operator (GSE) covers these costs by setting a small tax rate on all –non-renewable energy production. This regulation has been criticized by the European Union because it considers waste incineration a renewable energy source.

Green Certificates: resembles "Cap and Trade"

The green certificate system is mechanism that grants certificates to producers of renewable energy for the first 15 years of operation. Demand for these certificates is created by requiring all energy producers to produce a small percentage of their total output with renewable energy sources, or buy certificates to compensate (Puopolo and Croce 2001). CHP systems do not seem to fall under this arrangement. As PV systems are covered by the "Conto Energia" this leaves solar thermal electric systems and solar-assisted CHP systems.

Further into the research the conclusion will be drawn that SA-CHP systems outperform thermal-electric systems that operate without natural gas firing (due to a higher efficiency). It is unclear to the researcher if SA-CHP systems will fall under green certificate or CIP6 regulations. Because it will probably be very hard to reliably determine what portion of electricity is generated using natural gas and what portion by solar, it seems unlikely that certificates would be granted. Further investigation into this matter is difficult for the researcher as most literature on the subject is written in Italian. The researcher will therefore assume that the GC and CIP6 are not applicable from this point onward, slightly risking an underestimation of economic performance.

Subsidies

Conto Energia: fixed mandatory feedback tariff for PV

The 'Conto Energia' is an Italian regulation designed for the promotion of photovoltaic solar systems. It was recently simplified and is comparable to the mandatory feed-back system that has been very successful in Germany. There is no longer a maximum subsidy per operator but instead the law states a maximum capacity of 1.200 MW (peak) that will be subsidized in total. The law presents minimum prices for electricity generated by photovoltaics. The tarifs are fixed for 20 years and will not be corrected for inflation.

The mandatory feedback price for non-integrated systems[1] with a capacity over 20kW is 0.36 €/KWh, about 4 to 6 times higher than regular electricity prices in 2006-2007. The law allows for self-consumption, which is important in the case of DSM Capua. (AEEG 2007)

For now, the Conto Energia is limited to photovoltaic systems but a similar regulation is under consideration that promotes solar thermal electricity sys-

[1] Not integrated with buildings

tems. For thermal systems (no electricity) there does not seem to be much progress with respect to structural subsidy schemes in Italy or any other European country.

5.6 Weather Conditions

Beam radiation

The map in figure 20 shows that the local availability of direct beam radiation is disappointing at Capua compared to the rest of the south of Italy. This seems to be caused by the proximity of the Mediterranean Sea and the Vesuvius.

At Capua, western winds and an additional sea breeze caused by a sea-land temperature differential provide an ample supply of humid air. The city of Napels and the Vesuvius provide extra condensation nuclei accelerating the formation of clouds in the area. The Vesuvius and the Apennine mountains can possibly cause extra formation of clouds by forcing humid air to rise and cool (with thanks to D. Van Dijke MSc).

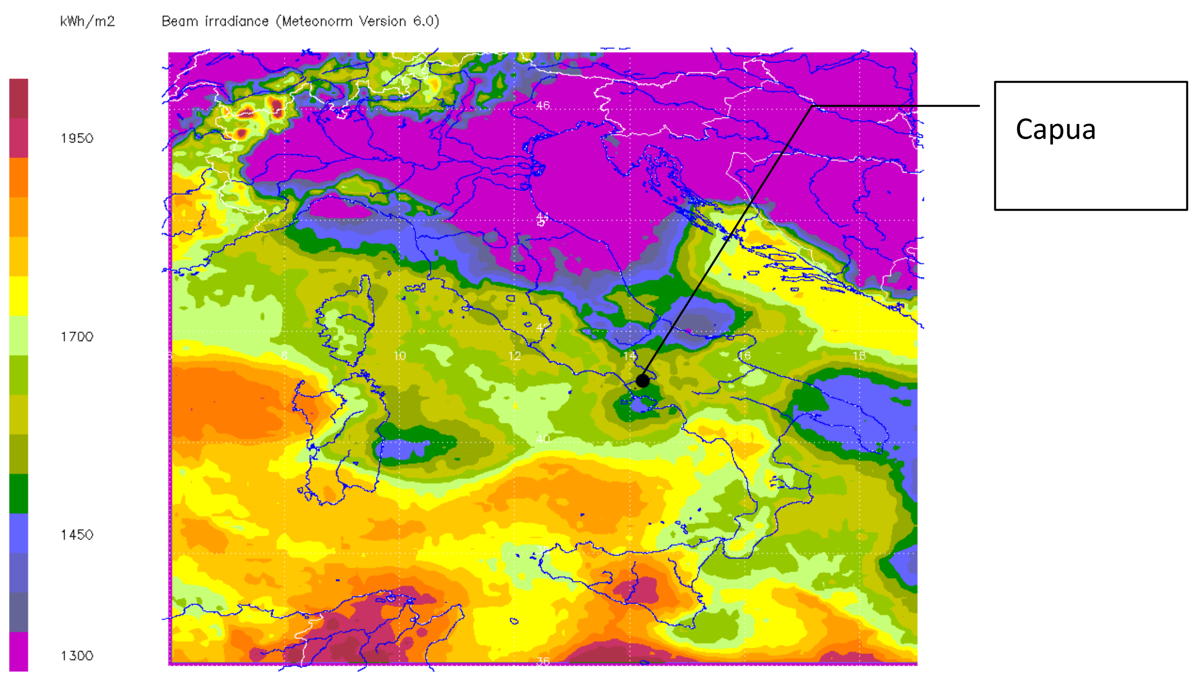


Figure 21, Yearly average direct normal radiation in Italy. (Meteonorm 2008)

Appendix C presents the beam radiation at Napels and compares it to California, USA. During the summer, the radiation intensity at Capua peaks and almost reaches the same levels as in California but during most of the year the amount is considerably lower.

Data type and source

Weather information can often be found in Typical Meteorological Year (TMY) format. NREL provides TMY data for locations throughout the world and states on its website: *“TMY data sets hold hourly values of solar radiation and meteorological elements for a one-year period that typify climate based on a much longer period of time”*

TMY (version 3) data of nearby Napels was used to analyze the situation at Capua during this research. (Available from http://www.nrel.gov/) Figure 21 illustrated that local variations can be substantial, but this was the best estimator found by the researcher. An uncertainty factor that influences the weather data was added to the model (that was developed during this study and that will be discussed in Chapter 8) and used during risk assessment.

Variation

Large variation in solar radiation intensity throughout the seasons can have effect on solar system performance. Figure 22 uses the TMY3 data to plot the average beam radiation intensity of a typical day for each month of the year. The figure illustrates that the solar intensity at Capua varies greatly. Not only is the solar radiation much more intense during the summer periods but additionally the sun rises much earlier and sets later.

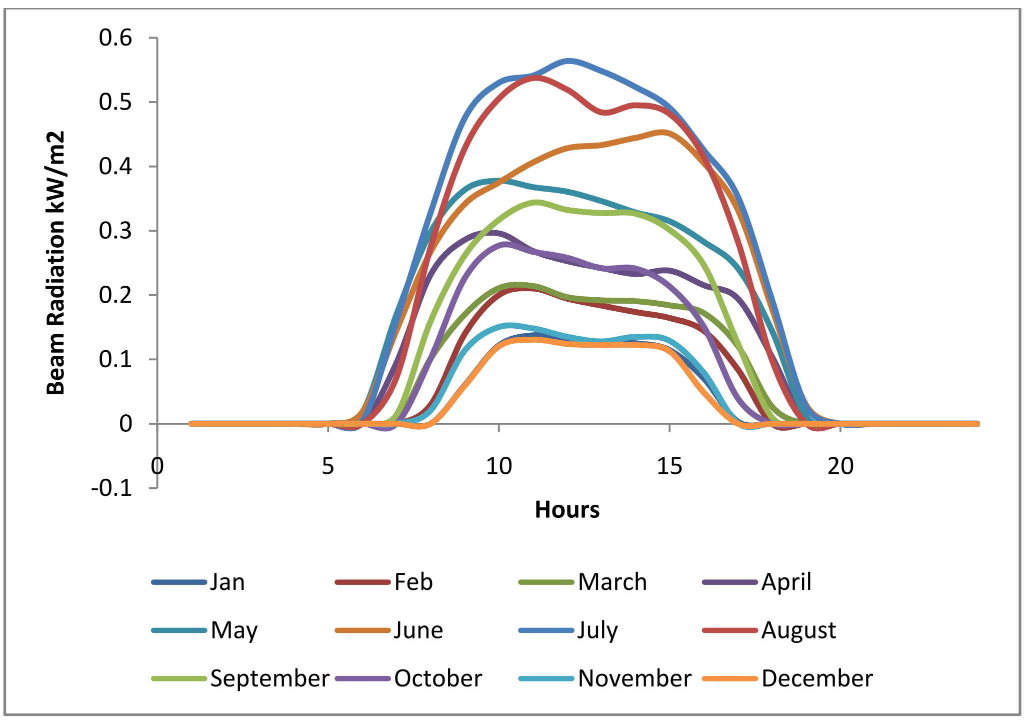


Figure 22, Beam Radiation

Extreme Weather

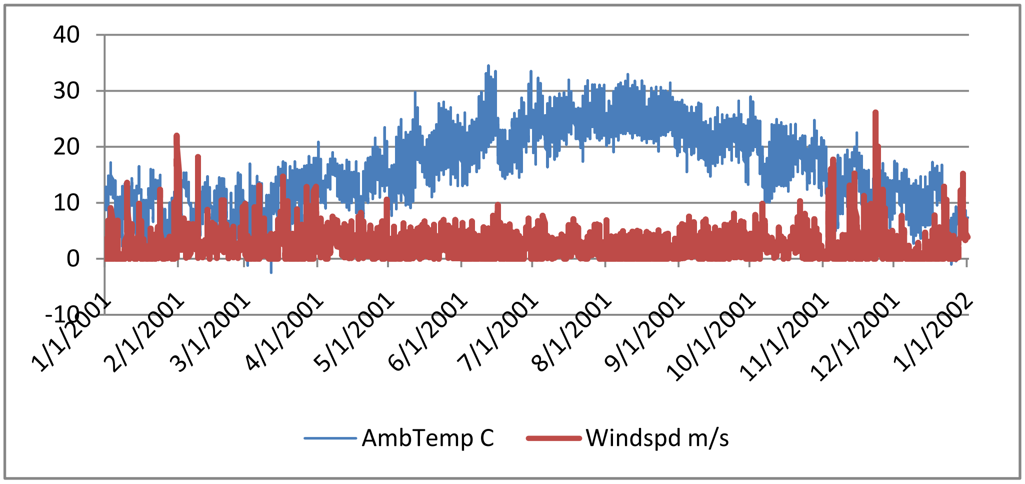


Figure 23, Extreme weather check

Based on the data in Figure 23, It is assumed that the solar technologies do not sustain freezing and or wind damage in 20 years which cannot be repaired within normal maintenance costs. It should be noted that TMY3 Data is generally not suitable for estimating extreme weather frequencies because outliers are removed when constructing the dataset. (NREL 2009) Therefore, it is recommended to consult an expert to assess this risk when necessary.

5.7 Grid Import Characteristics

Gird characteristics refer to the carbon dioxide emissions and fossil fuel consumption that relate to the import of electricity from the grid. Importing electricity from a highly efficiency grid results in lower green house gas emissions. This is beneficial for the industrial facility as a whole but not for solar power as an alternative source of energy: solar power becomes more valuable when importing from the grid is relatively more polluting.

Security of supply from both the natural gas as well as the electricity grid can , in some cases, also become an important factor. Disruptions can be costly and a solar design can increase security of supply. However designing solar energy systems that are suitable for stand-alone operation for an extended period poses many extra difficulties and can require large extra investments in energy storage.

5.8 Status of Key Performance Drivers

Key Performance Driver	Status/Assumption
1 Electricity Price	Exp = 0.11 Euro/KWh
2 Natural Gas Price	Exp = 0.35 Euro/KWh
3 Global Radiation	TMY Napels (timeseries)
4 Direct Beam Radiation	TMY Napels (timeseries)
5 Operating Temperature	140+ ^{O}C
6 Eff. of local elect .grid	Measured by GHG emission due to electricity import from Italian grid = 0.6714 Kg/KWh (Source RETSCREEN)
7 Heat demand pattern	Estimated equal to NG pattern daily 2006-2007 looped
8 Electricity demand pattern	Daily 2006-2007 looped
9 Direct subsidies	none
10 Feedback tariff subsidies	Conto Energia for PV 0.36 Euro/KWh
11 Extreme Weather	Assumed not damaging in 20 years.

5.9 Chapter Summary

The environment in which the solar design would operate was investigated in this chapter. The Key Performance Drivers that were previously identified as the most important factors that determine the performance of solar systems were thus investigated in detail.

Information about the status of these exogenous conditions is required in order to be able to simulate and predict the performance of these technologies at DSM Capua.

The investigation started with the structure and energy demand of the DSM production facility. Options to integrate solar technology within this system were briefly discussed. In addition, a possible option to reduce the boiler pressure of the current system to increase energy efficiency has been identified.

In addition, the investigation of the weather conditions at Capua, and comparison with other locations, led to the conclusion that these might not be very favorable. The proximity of the Vesuvius and the Mediterranean Sea appear to cause a local area of relatively low direct normal radiation. This is not favorable for concentrating technologies.

Table 5, Electricity and Natural Gas at DSM Capua

	Natural Gas	Electricity
Value of 1 MWh at 2006 prices	34 Euro (92.5 m^3)	110 Euro
Annual Average Consumption rate	5.7 MW	5.0 MW
Total Annual Costs	1.7 M Euro	4.8 M
Related annual GHG emissions (CO_2 equivalents)	$8.3 * 10^6$ Kg	$29.3 * 10^6$ Kg

The investigation of energy prices led to the identification of a gap between what DSM has been paying and what the AAEG (energy authority) reports industrial consumers should have been paying. This can easily be caused by local variations in energy prices, which can be substantial in Italy due to limited transport capacity; nonetheless, the researcher recommends further investigation.

Chapter 6. Basis of Design

6.1 What is a Basis of Design?

During the process of analysis, various important aspects have been investigated part by part, in order to prepare for the more subjective task of designing. First these findings are condensed and combined to form a basis of design (BOD). The BOD structures the results of the analysis and presents the following:

A. It defines the design space. The collection of all the variables that the designer can influence and that will be considered while designing. (for example scale as % of available land area)
B. It defines the objectives: statements of what the designer wants to achieve by changing variables in the design space, measured by performance indicators. (for example maximize CO_2 reduction)
C. It defines the constraints: The limitations that the design has to fulfill in order to be valid measured by performance indicators (for example the minimum CO_2reduction must be 10%)

In addition to these three aspects of a traditional BOD, a set of exogenous conditions was also defined. This is analogue to the adaptation of the meta-model of design as described in the introduction.

D. It presents the *exogenous conditions*. The collection of assumptions about externally given factors and future developments. These assumption are needed because the performance of a design depends on the environment it operates in. (for example the gas price is assumed to be constant at 0.37 Euro/m^3 over 20 years).

6.2 Design Space Overview

Table 6, Design Space

Variable	Description	Considered Range
Technology Type	Industrial Solar Power Technologies, and Combined Heat and Power.	(0) Business as Usual (1) Photovoltaics (2) Concentrated Photovoltaics (3) Solar Ponds (4) Flat Plates (5) Evacuated tubes (6) Hybrids (7) Linear Fresnel Heat (8) Parabolic Troughs Heat[1] (9) Solar Thermal Elec. Generation (10) Solar Refrigeration (11) Solar Assisted-CHP (12)CHP (13) Dish Sterling (14) Power Tower (15) Solar Furnace
Scale	Size of the solar energy system measured by the land area it occupies expressed as a % of the available land area (65000 m^2)	0-100%
Capacity (CHP ONLY)	Size of CHP. Here CHP scale or capacity is defined as the maximum energy consumption of a CHP plant. Alternatively It can be calculated by adding the electric output, the heat output and (thermal) losses.	3MW - 20 MW or 0 MW (no CHP)[2]
Electricity ratio (CHP ONLY)	Sometimes referred to as heat-ratio or electric efficiency. It is maximum ratio of electricity output divided by heat output.	0-1 but limited by available technologies

[1] Parabolic troughs can also be used for electricity generation via a generator but this falls under technology (9) or for refrigeration (10) or in combination with CHP (11).

[2] Below 3MW peak capacity investment cost scaling should be revised but a scale of 0 (no CHP) is also considered.

6.3 Design Objectives Overview

Table 7, Objectives

Factor	Description	Objective	Constraint	Unit
Net Present Value	Net Present Value of future cash flows minus investments generated by the investment over a lifespan of 20 years relative to business as usual	Maximise	> 0	Euro
Payback Period	Payback period. Time from investment until recovery of all investment costs due to cash generation or variable cost reduction.	Minimise	< 10	Year
GHG emission Reduction	Green House Gas Emission reduction. Expressed as percentage reduction of yearly Business As Usual emissions.	Maximise		%
Fossil Fuel consumption Reduction	Fossil Fuel Consumption reduction, measured in TONS of oil equivalent expressed as a percentage of BAU. Thereby combining Natural gas and Electricity consumption.	Maximise		%

6.4 Design Constraints Overview

Table 8, Design Constraints

Factor	Description	Constraint	Unit
Initial investment costs	The initial investment costs of a solar investment pilot project should not exceed 5 million euros. However an investment in CHP (plus solar) should not exceed 10 Million Euros.	< 5 Million	Euro
Location	Location restricted to DSM, Capua Italy other location are not considered.	DSM, Capua	
Land area	Total Land area available for energy project on-site.	< 65000	m^2
Grid connection	The facility should remain fully grid connected. That is the connection to the Italian electricity grid must by of sufficient capacity to be able to supply fully during peak demand.	Full Electricity	

Technology type	Only solar energy driven or solar energy assisted systems are under consideration plus CHP.	Solar Energy & CHP
Commercial Availability	The technology should be widely commercially available and proven.	Proven & available

6.5 Exogenous Conditions Overview

Factor	Description	Distribution Type	Value[1]	Unit
Electricity Price	Natural Gas Price development over 20 years. Assumed constant over time. Price as paid by DSM Capua.	Normal	Exp: 0.11 SD: 10 %	Euro/KWh
Natural Gas Price	Electricity Price development over 20 years. Assumed constant over time. Price as paid by DSM Capua.	Normal	Exp: 0.35 SD 10 %	Euro/m^3
Global Radiation	Data from one Typical Meteorological Year at Napels	Time Series	TMY Napels	W/m^2
Direct Beam Radiation	Data from one Typical Meteorological Year at Napels	Time Series	TMY Napels	W/m^2
Minimum Operating Temperature	Minimum temperature of heat that can be useful to the industrial process.	Constant	120	^{0}C
Efficiency of local electricity grid: (GHG Emissions)	Determines GHG emissions that relate to the import of electricity from the local grid.	Constant	0.6714	$Kg_{CO2\ Eq.}$/KWh
Heat demand pattern	Net Heat demand of the industrial facility	Time Series	Section 5.3	MWh/day[2]

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[1] Exp=Expected Value, SD=Standard deviation, Min= Minimum Value , Max= Maximum Value.

[2] The data set measured daily consumption in Mwh. The model automaticly converts to the more obvious unit for power: MW.

Electricity demand pattern	Net Electricity demand of the industrial facility	Time Series	Section 5.3	MWh/day
Direct subsidies	Direct subsidies that essentially lower the initial investment costs.	Constant	0	Euro
Feedback tariff subsidies	The subsidized feedback price that DSM receives if it sells PV electricity	Constant	0.37	Euro/KWh
Feedback tariff	The non-subsidized feedback price of electricity	Constant	85%	Fraction of electricity price
Extreme Weather	Conditions that have a high chance of damaging solar design alternatives. Extreme winds and minimum temperatures	Wind speeds & Ambient temperature	n.a.	n.a.

6.6 Chapter Summary

The results from investigating sub questions 1, 2 & 3 were combined into a BOD (Basis of Design). A BOD normally presents the objectives, constraints and design space of a project. In this case the BOD also presents the assumptions and scenarios about the operating environment (exogenous conditions) that the designer has no control over but need to be used when developing models and test the designs.

A BOD thus defines what a design is set to achieve, defines how to measure performance, defines when a design is acceptable, defines what design space will be considered and additionally presents in what environment the design is expected to operate. The data in it forms the basis on which the design process of PART III starts.

PART III : Design

Chapter 7. Screening

Research question:

Sub question 5. What are the most promising solar energy systems for application at Capua given the constraints?

The main goal of the screening method is to limit the time required for detailed modeling. The procedure will exclude design options that do not fit the situation at DSM Capua, thereby limiting the amount of alternatives that need detailed analysis. Care is required to avoid excluding technologies prematurely.

Reduce number of technologies that need detailed modeling.

7.1 Screening Method

We start off with the fifteen different technologies defined in the BOD, and then check using various tests whether they can possibly be interesting at DSM Capua. The tests are designed to be rather simple and not require detailed modeling, the point of the screening is to avoid spending time on detailed analysis when quick screening can illustrate that a technology is not applicable.

Start with 15 technologies from BOD

The screening criteria are derived from the criteria as stated in the BOD. Each criterion is assessed on a pass/fail basis. Sometimes it was unclear whether an alternative should fail or pass a test. If this is the case the screening table shows the label “unclear”. An unclear test result will not result in exclusion. A design alternative will immediately be excluded from detailed analysis if it fails one or more of the tests.

Exclude tech if it fails one or more tests

Failing any of the tests simply means that a design alternative is unlikely to be interesting at DSM Capua. It is important to note that this screening is thus not an assessment of a technology in general. It is possible that design alternatives failing this screening test are highly applicable at other locations!

Screening is not an assessment of a technology in general

The tests and test results are discussed per criteria rather than per design alternative. The results of the screening procedure are summarized first before each test in the procedure is discussed in subsequent sections.

7.2 Screening Results

Table 9, Screening Results.

	(A) Commercial Availability	(B) Elec. / Cold and or heat above 100 ^{o}C	(C) Applicable at scale below 65000 m^2	(D) Minimum investment below 5M Euro	(E) Not extremely likely to be outper-formed	(F) Analysis tool available	PASS?
(1) Photovoltaics							YES
(2) Concentrated PV					fail		NO
(3) Solar Ponds		fail					NO
(4) Flat Plates		fail					NO
(5) Evacuated tubes						fail	NO
(6) Hybrids	fail				fail	fail	NO
(7) LF Heat	unclear	unclear				fail	NO
(8) PT Heat							YES
(9) STEG					fail		NO
(10) S- Refrigiration	unclear					fail	NO
(11) SA-CHP	unclear			unclear			YES
(12) CHP							YES
(13) Dish Sterling					fail		NO
(14) Power Tower	unclear		fail	fail		fail	NO
(15) Solar Furnace	unclear	fail		unclear		fail	NO

Table 9 shows the results of the screening procedure that has been followed. Each of the tests will be discussed briefly in the following sections. Technologies fail the screening completely if they fail one or more of the tests.

The fifteen technologies can come in different forms and this can make it unclear whether a technology should be excluded or not. Because some tests are difficult to base on well-defined quantitative indicators (such as commercial availability), there remains room for discussion. Other researchers can thus make other pass/fail decisions. In addition, the screening should be revisited if technologies are further developed in the future. Nonetheless, the table clearly illustrates which technologies were selected for detailed analysis and why others failed.

7.3 Considered, but rejected, tests.

Some criteria and tests were considered, but not used during the screening. For example, DSM Capua at one point in time asked to add a reliability test to the screening procedure. The idea was to identify technologies that were highly unreliable and should therefore be excluded. Indicators such as mean time between failures (MTBR) or maintenance costs were considered. Unfortunately meaningful execution of such a test proved very difficult.

The first problem was that solar technologies can be unreliable in the sense that energy production stops because of failures but also because of weather conditions. What complicates things is that that a failure can coincide with bad weather or night times and that some technologies are much more affected by changing weather conditions than others. Additionally, the costs of failure differ between electricity and heat systems (as the value of the energy carrier that they replace varies greatly). The same is true for the costs of repair. Additionally (and probably because of the previous factors) data about solar energy system reliability is hard to come by. Reliability and costs of failures seem not to be a characteristic of the technology alone, but are dependent on local conditions. Consequently, it is impossible to give any meaningful recommendations without detailed analysis. These criteria therefore proved inappropriate for a screening procedure.

For the same reason tests regarding: investment costs, operational costs, subsidies, carbon dioxide emissions, and net present value were rejected.

7.4 TEST A (Commercial Availability)

Is the technology commercially available?

DSM made clear that technologies used at Capua must be commercially available and thereby “proven technology”. Low commercial availability could also cause maintenance problems if the technology producer is located far from the DSM production location and specialist help is required.

Defining a clear test for this constraint is difficult. Therefore a simple internet search for off-the-shelf products or demo projects was used to assess commercial availability. This was combined with an qualitative assessment of development status found in the Ullman Encyclopedia of Industrial Chemistry (Luther, Nast et al. 2000) .

Many technologies are clearly commercially available. A multitude of manufacturers can be found producing PV, solar ponds, flat plates, evacuated tubes and parabolic troughs systems. C-PV are commercially available but make up a very small portion of world PV production, only 0.1% in 2005 (Lewis 2005).

Commercial availability of large-scale systems such as a central receiver system is hard to asses as these are never of-the-shelf technologies. This does not necessarily mean that they cannot be produced on demand by specialist companies.

Solar refrigeration technologies are commercially available for residential use (air-conditioning) but availability of industrial systems remained unclear. Examples have been found where this technology is used, for example on large farms, but these were almost all experimental projects.

Hybrid technology that simultaneously produces heat and electricity is the only technology among the 15 that was excluded based on this test. This technology is not yet commercially available, but even if it becomes widely available, this technology failed other screening tests as well.

7.5 TEST B (Energy Match)

Is the design alternative able to produce either electricity, cold and or heat above 100 °C ?

This test is about matching demand and supply. At the production facility, there is demand for electricity, cold and heat above 100 °C. Because of utilization of waste heat from the air compressors the site has no net heat demand below 100 °C. The production site requires 140 °C steam. Natural gas is used to heat the boiler water up to at least this temperature. This has some very important consequences because in general lower temperature solar systems are cheaper to buy and operate.

They operate at higher efficiencies because the low temperature differences with ambient causes less heat dissipation. At the same time, staying below 100 degrees means that water can be used as a heat transfer fluid without causing pressure problems. Nonetheless solar ponds and flat plate technology must be excluded. These typically do not generate heat of sufficient temperature to fulfill heat demand at Capua.

The same holds for hybrid systems, these also generate low temperature heat but this technology also produces electricity and therefore passes this particular test. Linear Fresnel concentrating systems are able to produce heat above 100 °Centigrade, but probably at very low efficiencies due to heat dissipation and the relatively low optical efficiency. This design alternative therefore scores “unclear” but nonetheless passes this test. Solar furnaces for direct powering of chemical processes and drying are not applicable at Capua, so this technology is excluded as well.

7.6 TEST C (Available land area)

This test is to check whether the available land area at the production location is sufficient for installing each particular technology. Many solar energy systems are very modular. Small units can be combined to build large scale systems. This is all but one technology passes this test.

Is the technology applicable at 65000 square meters?

Only central receiver systems, better known as “power towers” are not applicable at this scale. Although 65000 square meters is quite large (it would be one of the largest industrial PV systems in the world for example) a power tower with a heliostat field requires an even larger land area. Not one example of a central receiver system was found that does not require a multitude of the available land area at DSM Capua.

7.7 TEST D (Minimum Investment & Modularity)

Because DSM made clear that a maximum of 5 Million Euros is available (for a solar power pilot project at DSM Capua) this test checks whether a design alternative can possibly be implemented below this maximum investment costs.

Is the minimum investment for a technology below 5 million Euros?

Due to the limited modularity the central receiver system was the only technology that must be excluded based on this test. Because this technology was already excluded in TEST 3, TEST 4 proved redundant. Note however that test 3 originates from a physical constraint whereas this test originates from the stakeholder goals.

Solar assisted combined heat and power systems can easily go above 5 million Euros of investment. However if the collector area is limited it is possible to create a design below 5 M Euros. More importantly, DSM clarified that a somewhat larger investment might be allowed when considering CHP and SA-CHP because it can be seen as more than a solar project alone.

7.8 TEST E (Outperformed)

If a design is very likely to be outperformed by another there is little reason to include it for detailed analysis. It will not become the design alternative of choice.

Is the design alternative extremely likely to be outperformed by any of the other alternatives?

Executing this involved the use of tools that are not yet fully introduced in this writing. In essence, the NREL SAM model was used to predict the electric output of PV, C-PV and dish sterling systems, under the weather conditions at Capua. As each of these systems produces electricity they are quite easy to compare without detailed modeling of the DSM production facility.

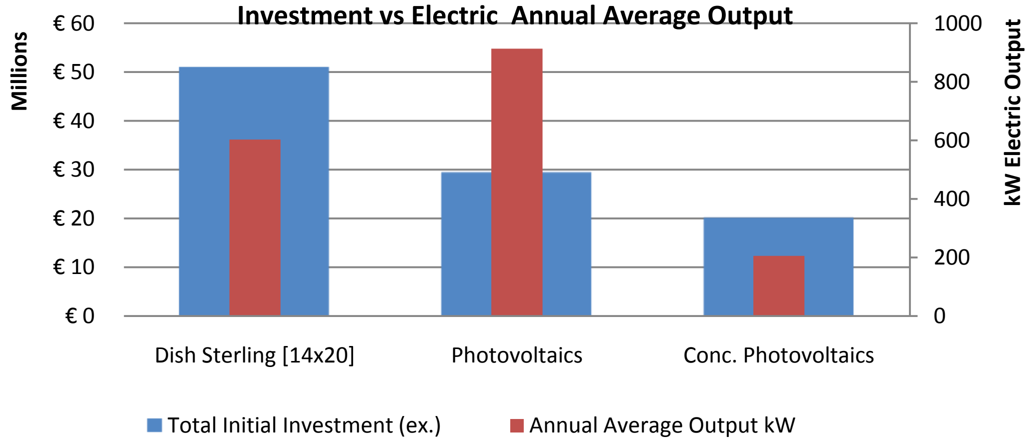


Figure 24, Rough Comparison of Direct Electricity Systems (Annual Average at 100 % of available land area at Capua)

If the annual average performance of these systems were about the same given the investment costs, detailed analysis would be needed. In such cases the timing of energy production would also become important, especially when volatile prices under spot market operation are considered.

Similarly heat and electricity solar systems cannot be compared without detailed analysis of market conditions and the production location. This test was therefore limited by comparing electricity solar energy systems, and heat systems, separately. Figure 24 shows the results of NREL -SAM simulations and illustrates that at Capua Photovoltaics easily outperform C-PV and Dish Sterling systems (due to weather conditions and typical system costs). Therefore C-PV and Dish sterling systems fail this test.

STEG systems (that in this writing) refer to systems that do not use fossil fuel co-firing are also excluded. SA-CHP technology would easily outperform these systems because it would be able to achieve much higher efficiencies by using natural gas to increase operating temperature. Thereby higher Carnot efficiencies are possible. At the same time, the ability to achieve a constant operating temperature means that utilization of waste heat would become much easier compared to STEG.

Additionally the utilization rate of SA-CHP systems would be much higher as the turbines can still be used even when there is insufficient solar radiation. STEG systems, as can be found in for example California, are often regarded interesting because at these locations heat storage, instead of natural gas, can be used to increase the utilization rate of the turbines. In the case of DSM Capua heat storage is not option because the heat production of a solar field at Capua is very unlikely to be higher than the heat consumption of the site at any given time (given the maximum land area and investment costs).

Hybrid systems are also excluded from further analysis. It was already established that hybrid systems do not produce heat of sufficient temperature to be used by the DSM production site. This technology was not excluded during TEST 2 because it also produces electricity. Nevertheless, these systems are most likely much more expensive than conventional PV panels when the heat they produce cannot be utilized.

Although this technology is excluded from further analysis, it is important to note that it has the potential to become interesting in the future. Under the right conditions these systems combine benefits of various other technologies. Technological advancement and costs reductions could make this an interesting option for industrial application.

7.9 TEST F (Analysis method)

Are there analysis methods available to predict the performance of the design alternatives within this research?

Compared to the other tests this one is clearly different in the sense that it has nothing to do with the technologies or the situation at Capua. It is simply about whether or not the researcher could find the (free for academic use) tools that could help assess the performance of a design alternative. If not, a design alternative must unfortunately be excluded.

There was no tool available to the researcher to assess the performance of a system using evacuated tubes and the same holds for refrigeration systems. To assess the performance of such systems at Capua use of a commercial solar analysis package such as TRNSYS or POLYSUN is required.

At the same time one should recognize that the high minimum temperature of the heat demand means that evacuated tubes would perform at reduced efficiency (although they are able to produce heat above 100 °Centigrade)

One must conclude that evacuated tubes, linear Fresnel systems and solar refrigeration systems could be interesting at Capua but this research cannot include them for detailed analysis. The tools to predict their performance with any accuracy are not available. Using rules of thumb to estimate performance based on literature and methods such as the F-chart methods developed by Klein (Duffie and Beckman 1991) proved impossible because these are not applicable when the heat production of a solar collector is only useful above 100 °C. Especially evacuated tubes could fit similar production locations quite well if boiler pre-heating is not done by other means. This technology is easily available, reliable and relatively cheap.

7.10 Chapter Summary

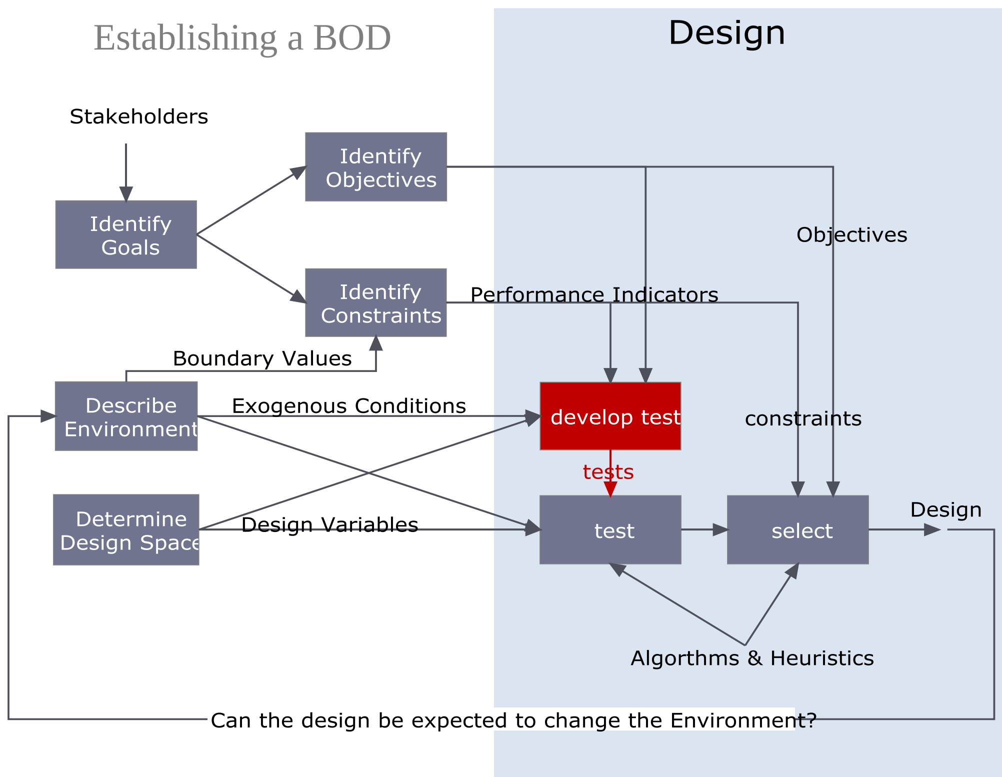
A screening method was used to identify which of the fifteen different solar technologies (that were found during a literature survey) are potentially interesting at DSM Capua. The point of the screening was to avoid spending time on detailed analysis when quick screening can illustrate that a technology is not applicable at DSM Capua.

The screening tests were developed based on physical constraints as well as DSM's objectives & constraints. Only four design alternatives passed the screening tests: Photovoltaics (1), Parabolic Troughs for heat generation (8), Solar Assisted Combined Heat and Power (11) and finally CHP without solar assistance (12). The actual performance of these systems however is unclear. Detailed modeling is required to predict their performance (measured by KPI's) at Capua. Developing the required models is subject of the next chapter. It is important to note that as technologies develop in the future more and more alternatives might pass this screening test if revisited.

Chapter 8. Modeling Solar Energy Systems

Before actually predicting the performance of the solar energy technologies (that passed the screening tests) at DSM Capua, a tool needs to be developed. This corresponds to the following research question:

What simulation toolbox can be developed to adequately estimate the performance of the selected design alternatives?



8.1 Model structure & functions

The toolbox that was developed in order to simulate the performance of the four remaining technologies can be divided up into five different *functions*. These are illustrated in Figure 25. The figure is followed by a brief description of each function.

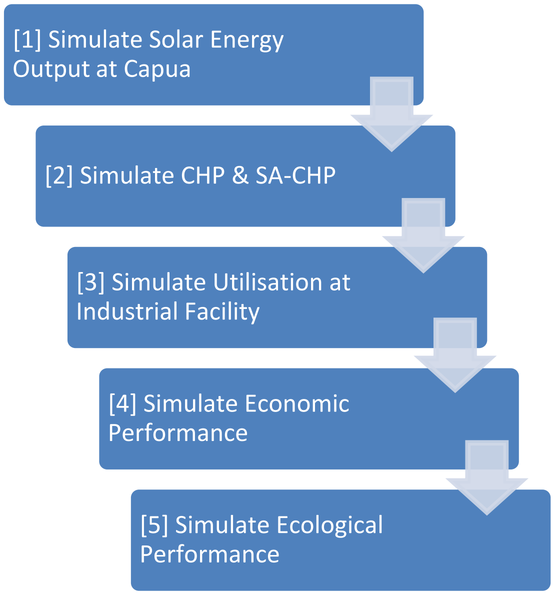


Figure 25, simplified overview of toolbox functions

[1] Energy Output Solar

First, the energy output of the four solar energy technologies must be calculated. In order to do this the design alternatives must be properly defined and appropriate simulation tools need to be found.

[2] CHP / SA-CHP

Second, a simulation of a combined heat and power system is required as well. This simulation should be able to use solar heat as input (from function [1]) to calculate the performance of the Solar Assisted CHP system.

[3] Utilization at Industrial Facility

Third, although tools that can calculate the energy output of solar energy alternatives were found (function [1]), these tools were not originally designed to simulate solar systems AT INDUSTRIAL LOCATIONS. An extra simulation function is required in order to determine whether the facility has an energy demand that matches the solar output. If, at a certain point in time, a solar energy technology generates more heat than that the industrial facility can utilize, it does not generate value. The research assumes that electricity can be exported at any time (at a high percentage of the electricity price, or subsidized in the case of PV).

[4] Financial accounting

Fourth, the portion of the energy delivered (by any of the four systems) that can be utilized by the facility generates economic value. The value of the fuel that is no longer required to fulfill demand, due to the investment, is used to estimate returns. Natural Gas & Electricity price scenarios and subsidy schemes are used to calculate the cash flows that relate to production of electricity and/or heat by the four alternatives. This is combined with other financial data such as operation costs, insurance costs, etc to determine financial performance.

[5] Ecologic "accounting"

Fifth, the solar technologies reduce the net consumption of either natural gas (thermal system) or electricity (PV system). The CHP / SA-CHP systems cause extra import of natural gas but can decrease the net consumption of electricity. This can be beneficial compared to importing electricity due to the utilization of waste heat and higher efficiency than the Italian electricity grid. This fifth model layer calculates fossil fuel consumption and green house gas emissions that are caused by the industrial process with the investment, and compares them to business as usual.

Complicating factors

This section explained the basic functions of the toolbox. Before continuing with explaining which software tools were used to perform these five main functions, it is useful to mention some complicating factors. First it should be noted that the toolbox is set up in such a way that it allows Monte Carlo simulations and stochastic input, second the toolbox includes a rough user interface that for examples allows to user to change the scale of an alternative during financial analysis (function [4]), without requiring the user to rerun simulations in function [1]. Lastly, the tool can be used to find an appropriate scale of investment [1] using evolutionary optimization algorithms. Appendix E lists limitations of the toolbox.

8.2 Software tools

Figure 26 shows the same five functions, but additionally displays the software tools and models that were used to perform each function. The figure not only illustrates how the tools relate relate, but indicates the information input as well. This illustrates that the data sets required by the toolbox relate to the status of exogenous conditions (and thus KPD's) that were discussed in previous chapters.

This figured is followed *by Table 10, Models and Usage*, which briefly describes the individual software tools.

[1] Maximizing NPV under stochastic assumptions, (only if there is an optimum).

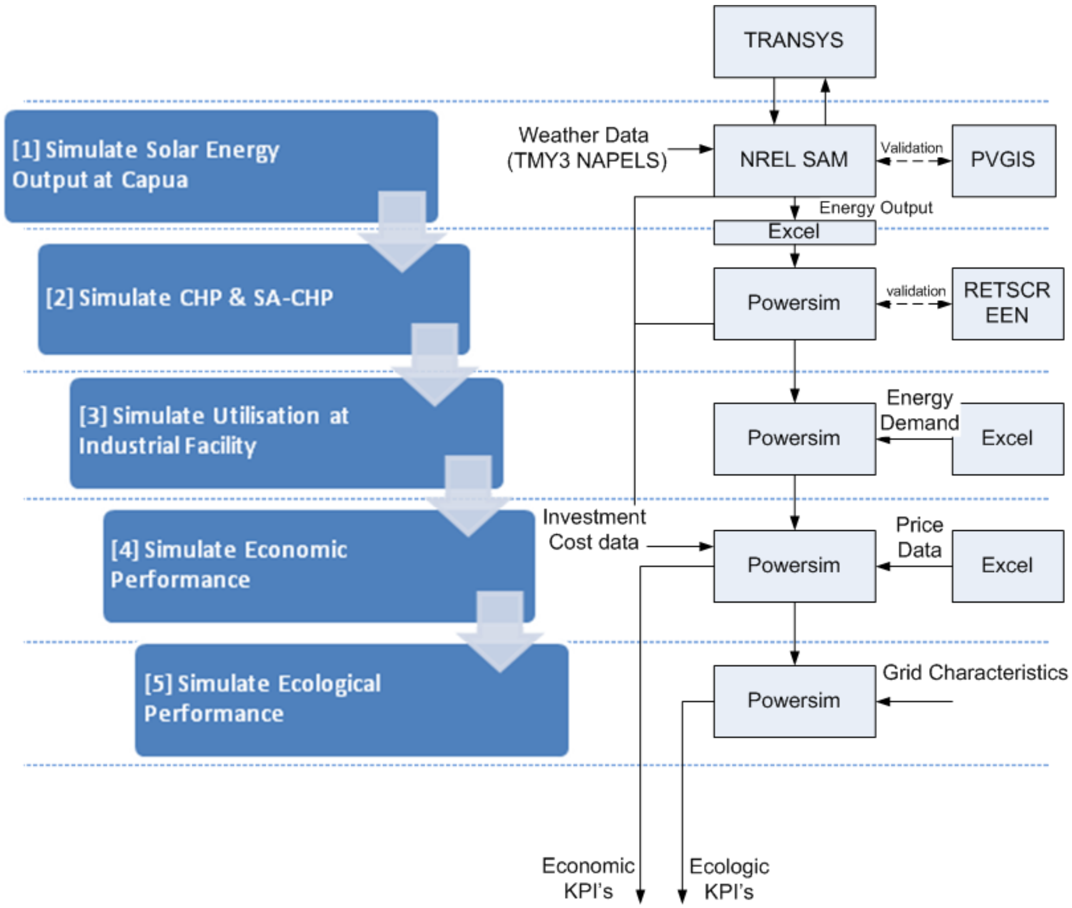


Figure 26, Model structure and software tools

The model can also calculate the performance of a combination of systems, which is due to a limited utilization of heat not necessarily equal to the cumulative performance of the elements alone.

Please note that the actual filestructure is somewhat different from the model-structure. For example, the multiple Powersim models are combined into a single file, for a more detailed view of the filestructure see Appendix D. The different software tools are introduced next.

Table 10, Models and Usage

Tool/ Model	Description	Note
TRNSYS	TRNSYS is a software package underlying NREL SAM. It performs the actual energy calculations required for the simulation of solar alternatives, but is not directly accessible in this toolbox. This tool is very often used and mentioned in solar energy literature. It is not freely available in a stand-alone form.	Commercially available from http://www.trnsys.com/

NREL- SAM	The Solar Advisory Model is frequently used during this study. SAM is a front-end for TRNSYS, and comes with a database of various solar alternatives, both PV and Solar Thermal-Electric. This tool is used to define design alternatives and calculates their performance based on weather data. Main output of this model is the daily electricity or heat produced per design alternative.	Freely available from National Renewables Energy Laboratory (USA) (www.nrel.gov)
PV-GIS	Map-based online tool that can predict the performance of PV systems on locations throughout Europe. This tool was only used to verify the results from the NREL SAM simulations. It is easy to use, but cannot calculate the performance of thermal systems.	Freely available from http://re.jrc.ec.europa.eu/pvgis/
RETSCREEN	Developed by Natural Resources Canada (governmental). This MS. Excel based tool can estimate the performance of CHP systems (among others) under various conditions. It is used to verify the results of the Powersim CHP simulations.	Freely available from www.retscreen.net
POWERSIM: CHP/CHP	The researcher developed a model within the POWERSIM system dynamics software package that simulates the performance of a CHP system at DSM Capua under various conditions. This model calculates the energy input and output of the system and can cope with solar assistance.	http://www.powersim.com/
POWERSIM: **Financial & Ecological accounting**	The researcher developed an accounting model that calculates the effects of integrating the solar alternatives within the DSM production system. It combines the technological performance of the design alternatives with the exogenous conditions to calculate key performance indicators such as NPV, Fuel Consumption and GHG emission reductions. It was used to perform Monte Carlo simulations and also to search for an optimal scale of investment (in the case of CHP).	(in reality the Powersim CHP and Accounting models, are integrated into one file)

Some of the tools are not used for what they were originally intended. Table 11 presents what a tool's general usage is, and compares it to how the tools were used in this particular research.

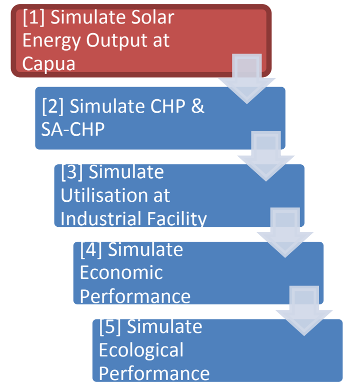
Table 11, General usage of tools versus purpose in this research

Tool	General Usage	Purpose in this research
TRNSYS	Detailed simulation and modeling of solar energy systems	Underlying engine of NREL SAM
NREL SAM	Provides front-end for TRNSYS and calculates the economic performance of	The alternatives were defined using the technology library. The energy

	various solar energy systems (delivering electricit) under United States Tax and incentives regulations.	output in the form of heat or electricity was extracted from simulation output (Kwh/day). Build-in economic analysis was ignored/bypassed
M.S. Excel	Spreadsheet Calculations	Database for storing energy output data, provide link between NREL SAM and POWERSIM
POWERSIM	System dynamics software tool	1. Simulation of CHP/SA-CHP 2. Financial Accounting 3. GHG emissions accounting 4. Optimisation (scale) 5. Monte Carlo simulation
PVGIS	Calculation of energy output of PV systems based on maps	Validation of NREL-SAM results for PV
RETSCREEN	Decision support tool for energy investments (renewable and conventional energy systems).	Validation of POWERSIM CHP model (and provided grid characteristics data for Italy: GHG emissions per KWh electicty imported)

Now that the structure of the model is clear, each of the five main functions is discussed in more detail in the following sections.

8.3 FUNCTION [1] Simulate Solar Energy output at Capua



NREL-SAM (based on TRNSYS) was used for calculating the energy output of various stand-alone solar alternatives under the weather conditions at Capua, either electricity in the case of PV systems or heat in the case of thermal systems. The results of the PV calculations were validated using PVGIS but the researcher was unable to find second tool to validate solar thermal simulations.

NREL-SAM screenshot

PVGIS screenshot

Detailed settings of the NREL-SAM (and PVGIS) simulations are stored in digital data files that will be distributed with this report. These can be reviewed using the (freely available) tools, however the main settings are presented in Table 12. The simulations are performed using settings that results in a full-area investment (65000m^2). The user can scale down the investment via Powersim later[1] .

NREL-SAM can be set up to simulate the performance of a thermal-electric system but not a thermal-only system. This was solved by extracting an intermediate model output parameter: *thermal energy to powerblock*[2]. This data depicts the heat output of the solar panels corrected for various losses in the system. The powerblock simulation was completely ignored, because NREL-SAM does not correct for the value of utilizing of waste heat. Instead Powersim covers CHP/ SA-CHP simulation, as will be discussed in section 8.4.

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[1] Using a simple linear approximation.

[2] Powerblock refers to all system components that are necessary to convert heat into electricity.

Table 12, Basic model settings (full area).

NREL- SAM (THERMAL)	NREL SAM (PV)	PVGIS (PV)
Panel: Luz LS-3 Mirrors (PTC), Scott PTR70 Absorbers **Number of modules:** 15 rows * 4 PTC's[1] **Tracking:** One axis **Weather data** (TMY3) Napels	**Panel:** Schott Solar ASE-300-DGF/50 EFG (mc-Si) **Number of modules:** 25.700 (results in 6.8MWpeak$_{dc}$) **Tracking:** one axis **Weather data:** (TMY3) Napels	**Panel:** (nonspecific) Crystalline Sili-con PV **Peak capacity**: 6.8 MW **Tracking:** one axis **Weather data:** (map-based) Napels

PVGIS was used to validate NREL-SAM PV model outcomes. The PVGIS is an online program designed for the prediction of PV system performance in Europe. It requires peak system capacity and location as input, and calculates electric output while optimizing placement and orientation and correcting for system losses.

Factor	NREL- SAM (PV)	PVGIS (PV)
Electric output (annual average)	954 kW	1004 kW

The number of PV collectors set in NREL SAM resulted in approximately 6.8 MW peak capacity for a full scale system (65000m^2). Based on this peak capacity, the PVGIS model predicts a 954kW annual average electric output at Napels. This calculated average compares quite well with the 1004kW estimation by NREL-SAM. A graph of the monthly energy output however illustrates that the two simulations somewhat differ (see Figure 27). PVGIS predicts a lower electric output during summer months but a higher output during winter months, (resulting in almost equal average output). The difference could be caused by how the tools optimize orientation. Nonetheless, these similar results build confidence in the NREL-SAM simulations and set-up.

[1] In this confiration rows are 15 meters apart. This is neccery for maintanance but putting them more closely together also results in higher shading losses.

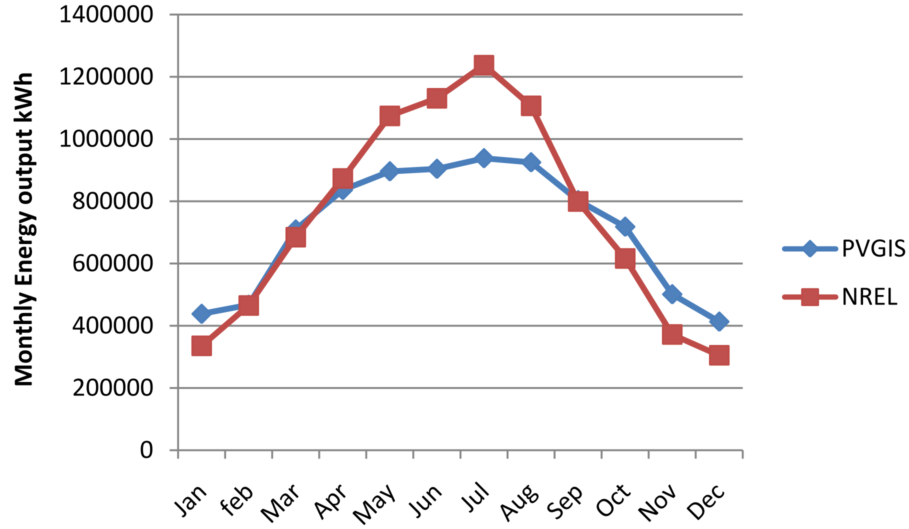


Figure 27, Simulation of a PV system in PVGIS versus NREL-SAM for validation purposes

Now that the energy output data was validated, the estimation of investment costs is investigated as well. NREL-SAM estimates investments costs for a full scale PV system (which is quite large) to be approximately 35 Million Dollars[1].

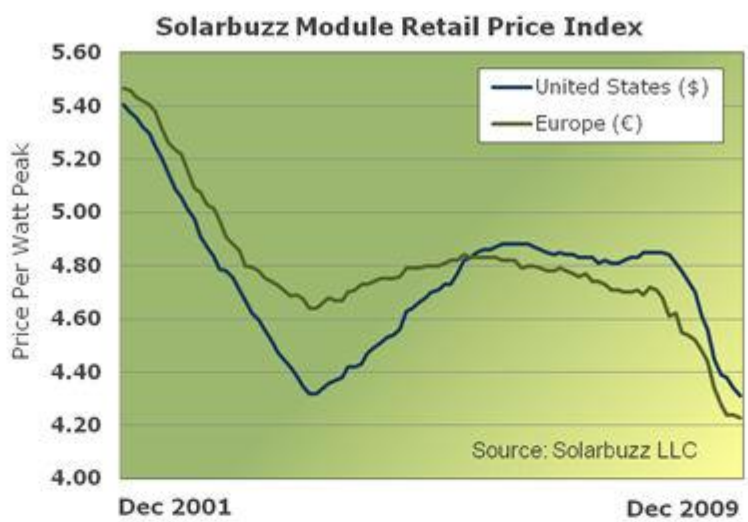


Figure 28, PV Investment costs data (solarbuzz 2009)

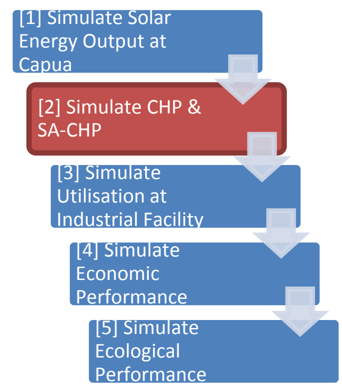
To check if these investment costs are realistic it was compared to another data-source. Price estimations by solarbuzz.com, a website that continuously benchmarks retail prices of PV modules produced in Europe and the United

[1] keep in mind that the powersim model converts this to Euros

States, are presented in Figure 28. A collector panel price of 4.2 dollars/W_{peak} times 6.8 MW_{peak} equals a total cost of 28.6 Million Dollars. This is somewhat less than what NREL-SAM calculated and it is likely that the costs in reality are still lower due to a large-order discount (this is quite common). NREL-SAM estimations, on the other hand, include some additional indirect costs such as for implementation and inverters that solarbuzz estimations do not include. Therefore, the researcher sees no reason not to accept the NREL-SAM estimations.

The energy flow data of the PV and PT alternatives are stored in a MS. Excel file, which in turn is connected to the other model functions.

8.4 FUNCTION [2] Simulate CHP/ SA-CHP



Powersim was used as tool to simulate the performance of a CHP system. The basic Building blocks used in Powersim (and in other System Dynamics modeling tools) are Levels and Flows. With these, a representation of some real world system is built, based on the idea that the structure of the system determines its behavior.

The structure of this part of the model is displayer in Appendix J. The figure in the appendix is unfortunately not very clear. This is caused by the fact that many extra factors are included in this part of the model. These factors are necessary for the operation of the user interface, risk assesment and are required for generating various graphs.

In essence, the modeling of the CHP is quite simple. The user first defines a maximum total capacity in MW. This is equal to the amount of fuel that the CHP maximally can consume at any given time. Then the model assumes that a certain portion of this energy is lost as waste heat, using an overall efficiency parameter.

The remaining energy is then partly converted into electricity, and the rest is heat that can be delivered to the industrial process. The ratio between the two is determined by the electric efficiency (or heat rate) of the design alternative (which is a turbine-generator design characteristic and is limited by the Carnot efficiency).

Heat rate data for a large collection of generators was plotted (Figure 29) based on data from http://www.gas-turbines.com/specs/heatrt.htm. This website collects data from buyers and manufactures of turbines on a voluntarily basis and could not be validated.

The model does not assume that the CHP unit is running at full capacity all the time. Instead, it is heat-regulated. The model automatically decreases the utilization rate when the CHP produces more heat than the industrial facility can utilize. A consequence is that the model reduces the production of electricity when waste heat cannot be utilized, even when this would be economically attractive. This can only be the case when the electric efficiency is high enough to compete with the national grid.

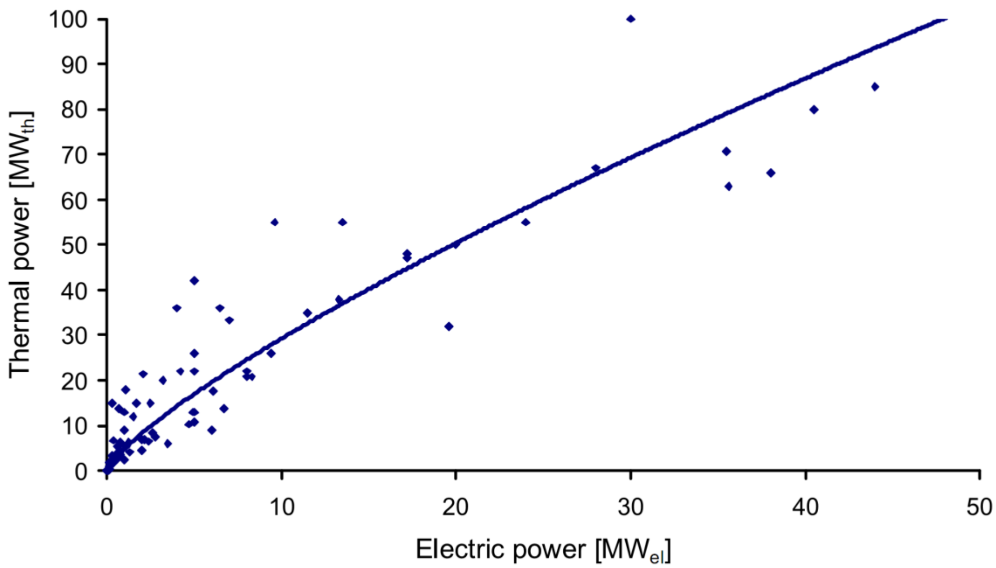


Figure 29, Electric efficiency plot, data from (Gasturbines 2009)

In the case of SA-CHP the model simply subtracts the heat output from the solar system from the heat requirement, and thus natural gas requirement, of the CHP system. The model allows the user to set a maximum portion of solar assistance at any given time. This can be useful because a large volume of relatively low-temperature heat cannot always be utilized by the CHP system.

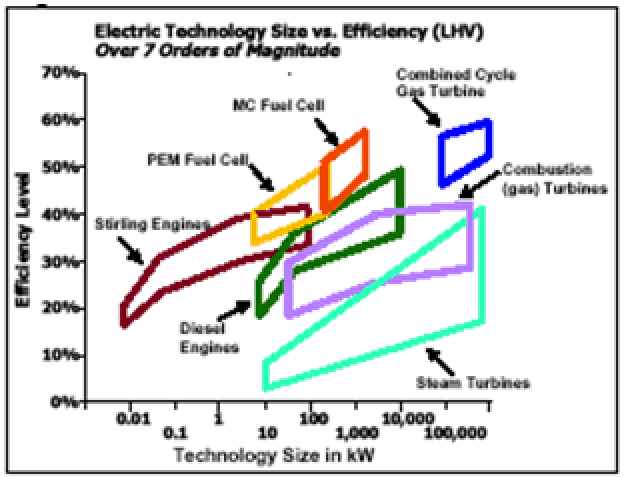


Figure 30 Efficiency of turbines versus scale. (northeastchp 2009)

The electric efficiency of the turbine-generator combinations proved a very important model setting. Therefore, values were used from two different sources: (northeastchp 2009) & (Gasturbines 2009). Figure 30 illustrates that, at the scale that is appropriate at Capua (between 1MW and 10 MW), steam turbines are not as efficient as diesel engines or direct combustion gas turbines. Fuel cells systems can potentially even be more efficient but application at above 1MW capacity seems rare. Combined Cycle Systems on the other hand are only applicable at larger scales. The higher investment costs of both Fuel Cells and Combined Cycle systems seem unnecessary when waste heat can be utilized. Diesel engines and gas turbines, on the other hand, are not more expensive than steam turbines, but cannot be integrated with a solar energy system.

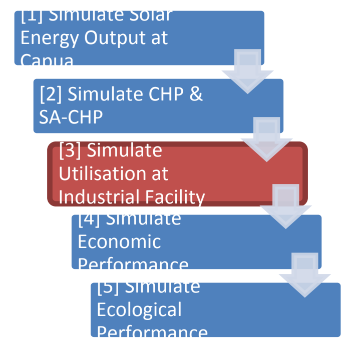
RETScreen was used as a secondary tool to simulate the performance of a CHP system and was compared to Powersim results. Monthly average demand was used in RETScreen whereas Powersim uses daily data. A test was performed with comparable 3.5 MW electric capacity CHP systems (equal to approximately 7 MW total capacity Electricity+Heat).

Table 13 illustrates that the comparison was also made with respect to CO_2 emissions, validating not only the CHP model function but also the GHG emission accounting in Powersim. The table shows that RETScreen estimates a somewhat higher electric output. This can be explained by the fact that the CHP in the Powersim model is heat regulated while the CHP in RETScreen is not. The Powersim model thus reduces the utilization of the CHP during the summer months while RETScreen does not. It should be noted that some data from the RETScreen library is used in the Powersim model, for example data about the efficiency of the Italian electricity grid. Validation of tool A, using tool B, that was also a data source for tool A, is not an ideal situation, but the best that the researcher could do.

Table 13, Powersim and RETScreen model output comparison.

	RETScreen	Powersim
GHG emission reduction	18.381 tCO_2	19.176 tCO_2
Annual Electricity production	25.754 MWh	23.744 MWh

8.5 FUNCTION [3] Utilization at Industrial Facility



Although important, this function is quite simple. The model assumes that electricity can be sold at any given time. The energy flow from the solar thermal system to the industrial facility on the other hand is limited by the heat demand at that point in time. The natural gas consumption of the boiler (under business as usual) is used as an indicator for heat demand. The model includes a setting to correct for efficiency improvements within the industrial facility that essentially lower net heat demand.

The model corrects for the fact that implementation of a CHP effectively increases heat demand, allowing the implementation of a larger solar field.

This research did not consider a heat storage system, mainly because the maximum investment funds do not allow a solar field of sufficient size to require a storage facility at DSM Capua. However, in other situations a heat storage system might substantially increase overall performance. Instead of wasting heat, the system would simply store it and use it during nighttime. This would require a much more complicated implementation of this model function.

8.6 FUNCTION [4] Simulate Economic performance

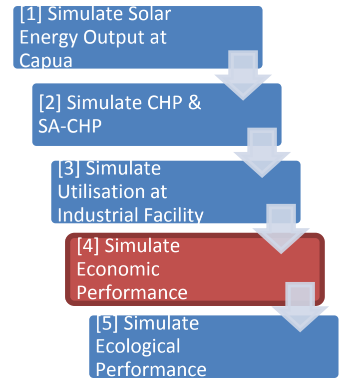
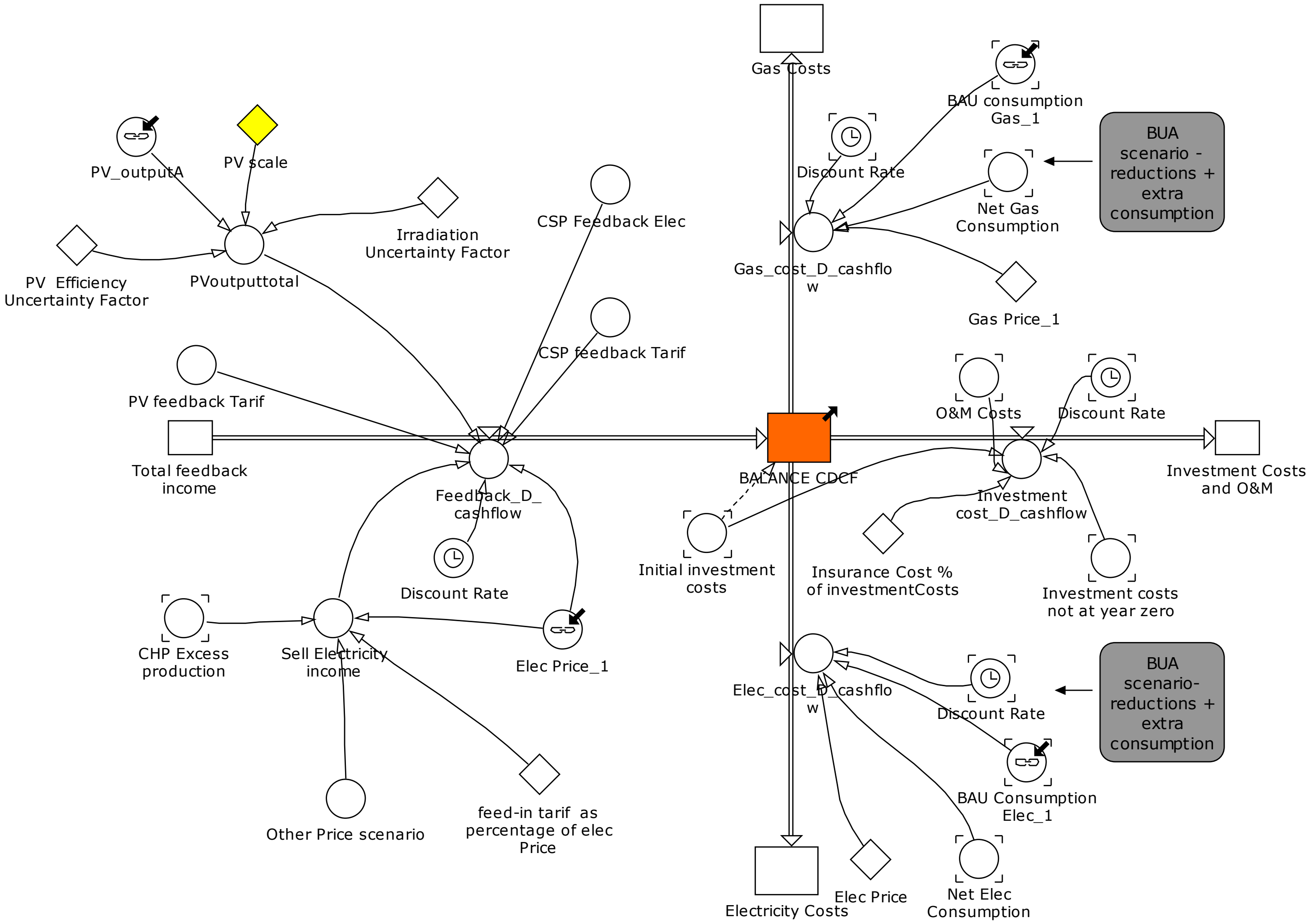


Figure 31 shows a simplified version of the core model that was used to assess the economic performance of various technologies. The basis of the model is simply calculating the costs of electricity and natural gas by multiplying the facility's import with respective prices. The resulting cash-flows are discounted by the discount rate. The sum of all discounted cash in and cash out flows is the result we are after. This variable is named BALANCE CDCF where CDCF stands for Cumulative Discounted Cash Flows. It seems easier to simply name this variable Net Present Value, (as is often done in similar cases) however that would not be entirely correct. Appendix G explains the difference between the two.

The upper and lower right quadrants of figure show the structure of calculating electricity and gas costs. The net consumption of electricity and gas are calculated by starting with a consumption scenario, (for example the recorded consumption of 2007 and 2008 in a loop) subtracting energy reduction (for example due to solar energy, or efficiency improvements) and adding extra consumption by new projects (for example gas turbine).

Figure 31, Powersim Model Core



Solar systems do no generate positive cash flows. These systems reduce the fuel consumption and thereby improve the negative cash flows that result from buying fuel. An early version of the accounting model simply compared the less negative cash flows with business as usual at the end of the simulation run. This approach however results in the problem that a higher discount rate (relating to higher risk) will increase overall performance because all negative cash flows are more strongly discounted.

The resulting net consumption at a certain point in time is therefore not directly multiplied by the energy price at that point in time. Instead, the model compares the net consumption with what the consumption would be without the solar system but under the exact same exogenous conditions. How much energy consumption was abated by the solar system is then multiplied by the respective price at each simulation step.

This approach is not directly the same as simply multiplying the solar alternative's energy output with the prices that DSM would have to pay if that energy was bought, because the facility might not be able to utilize that energy at every point in time.

Gas and electricity costs (cash-flows) are then discounted and subtracted from Balance CDCF. In addition there is an extra outflow called Investment Cost, which is used to calculate the present value of investments that are made during the simulation (but not at t=0). Lastly, a fourth cash flow is used to calculate the income that is generated when surplus electricity is fed back to the grid (possibly subsidized).

Algebraically:

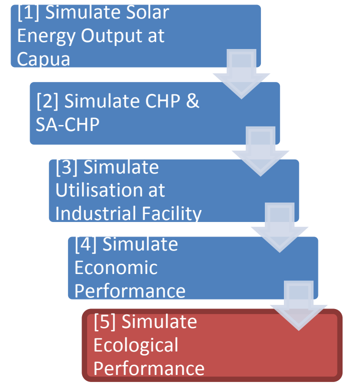
$$Balance\ CDCF = I + \int_0^t \frac{A(t) + B(t) + C(t) + D(t)}{(1 + wacc)^{year\ (t)}}$$

- Where:
- I = The initial investment
- wacc= weighted average costs of capital (discount rate)
- A=Electricity Costs
- B=Natural Gas Costs
- C=Operational costs+ other investment costs
- D=Surplus feedback income

The solution of the integral is approximated by the model with a first order Euler integration method with a 1 day time-step. It is important to note that all of the discussed factors vary over time. If these factors would not vary over time (and sometimes interact), the calculations could have been performed by using a spreadsheet program.

The model assumes that the solar system becomes operational and generates positive cash flows from the moment of investment. The model can be improved by including a construction-time where the investment is made but the system not yet up and running. Secondly, this method implicitly assumes that DSM funds are used for the investment. If it is possible to fund the project with a loan one can possibly generate positive cash flows from year 1, however funding strategies other than full direct investment lie outside the scope of this research.

8.7 FUNCTION [5] Simulate Ecological performance



Installing a CHP system and thereby increasing the import of natural gas while decreasing the import of electricity is ecologically attractive whenever the carbon dioxide emissions of a conventional electricity plant are higher than that of the (on-site) CHP system. This is often true due to the utilization of waste heat and/or higher efficiency and lower transmission losses.

Replacing imported electricity by self-generated electricity therefore can be hugely ecologically beneficial, regardless of the fact that the on-site carbon emissions increase. While calculating ecologic impact one needs to look further then the production site and include the characteristics of the Italian energy system.

By doing so, one calculates the ecological impact that is a consequence of the production system instead of calculating the impact at the production location only. One should realize that the modeling results (and actual performance) therefore depend on assumptions about the operating environment as much as on assumptions about the design alternative or the production process itself

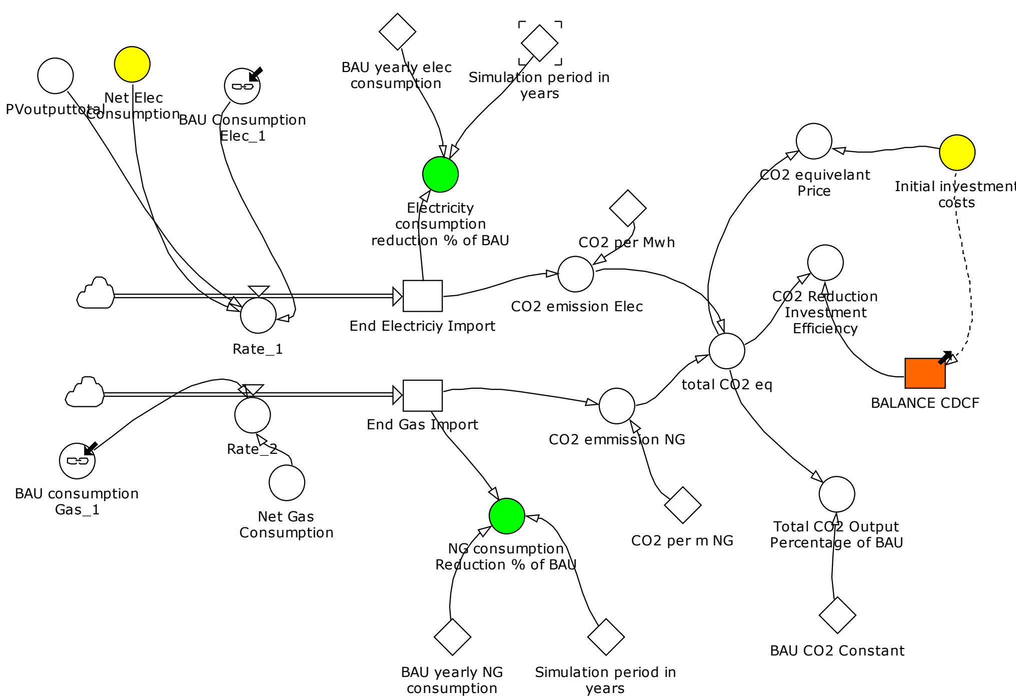


Figure 32, GHG and fuel consumption accounting

Figure 32 displays the Powersim model structure that is responsible for calculating the amount of green house gas emissions that relate to electricity and natural gas consumption. The model compares this to BAU automatically. This results in a calculation of the GHG emissions in Kg Carbon Dioxide equivalents and the relative reduction compared to BAU.

8.8 Verification & Validation

The terms validation and verification are sometimes used interchangeably but have different meanings in this research. NASA provides clear definitions:

Verification is defined as:

> *The process of determining that a model implementation accurately represents the developer's conceptual description of the model and the solution to the model. (NASA 2008)*

The process of verification is only very briefly discussed. Model assumption values were checked between simulation runs. The structure of the different model parts were investigated multiple times. Powersim's requirement that all units (of the different factors) are clearly defined and correctly relate to each other, proved valuable as incorrect model connections often result in illogical or incorrect units. This helps to spot mistakes.

Validation is defined as:

> *The process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model. (NASA 2008)*

The process of validation will be discussed in more detail. It is important to build confidence in the model and the model results. The main approach to validation was to try to use different tools to model the same situation when possible, and compare results. This was already discussed in the previous sections, but will be summarized here.

The simulations of the NREL-SAM and underlying TRNSYS tools were often validated by other researchers that compared simulation results to experimental data (Kalogirou and Papamarcou 2000; Bony and Citherlet 2007; Fan, Dragsted et al. 2007; Loutzenhiser, Manz et al. 2007). This builds confidence in the model itself, but this does not automatically mean that the tool was properly configured within this particular research. Therefore, another tool. Namely PVGIS was used to simulate a comparable system under the same circumstances. Investment costs were compared to data from solarbuzz.com

A second tool to validate the performance of the thermal system could not be found.

The Powersim model output with respect to the CHP system (not SA-CHP) (energy output and carbon dioxide emissions) were validated using a second tool called RETScreen.

The financial model functions were first investigated by comparing the models calculation of variable costs (fuel costs) with the actual costs during 2006-2007, these matched accurately.

Extreme value tests (structure oriented) were performed throughout the development of the Powersim models. Extreme model setting were set, for example a very large CHP system, and the simulation results were investigated in order to check for unexpected results. This approach helped to identify and solve many issues during development.

An overview of validation activities is presented in Table 14.

Table 14, Validation of data in various stages of model development.

Factor	Source/Tool:	Validation with:
PV electric output	NREL-SAM	PVGIS
PTC thermal output	NREL-SAM	none
PV investment costs	NREL-SAM	Solarbuzz.com
PTC investment costs	NREL-SAM	none
CHP energy output	Powersim (custom made)	RETScreen
CHP investment costs	northeastchp.org	gas-turbines.com
CHP heat rate	northeastchp.org	gas-turbines.com
SA-CHP heat rate	northeastchp.org	gas-turbines.com
SA-CHP investment costs	Assumed SA + CHP	none
SA-CHP energy output	Powersim	none
Financial accounting	Powersim	Compared to actual costs 2006-2007 & extreme val-

		ue tests
Ecological accounting	Powersim	CHP compared to RET-screen, others not validated

8.9 Explaining choice for Powersim

Before continuing with the chapter summary, this section explains the choice to use a system dynamics software package in this research.

Alternative modeling approach

A completely different modeling approach based on linear programming and network optimisation whereby the model was aimed at finding the most efficient route through a network of energy conversions (via technologies) was attempted first, but failed due to time-dependence and non-linearity. The intended model structure can be found in Appendix M.

"Simulations in Powersim Studio are based on system dynamics. System dynamics is a computer-based simulation modeling methodology developed at the Massachusetts Institute of Technology (MIT) in the 1950s as a tool for managers to analyze complex problems" (Powersim Studio 7 Manual, introduction to Powersim)

The basic Building blocks used in Powersim (and in other System Dynamics modeling tools) are Levels and Flows. With these, a representation of some real world system is built based on the idea that the structure of the system determines its behavior. Feedback loops within these structures are usually extremely important. The dynamic behavior of a complex system and the effects of measures taken to influence it can be unpredictable due to feedback loops.

Getting insight into these effects is usually the main purpose of building a system dynamics model with the help of a software package such as Powersim. The models work by calculating increments in levels and flows per time step. If the time steps are small enough the model results approach the solutions that explicit integration calculations would yield, but provide much more flexibility without being limited by the complexity of analytic mathematical calculations.

The choice to use a system dynamics software tool, was largely based on the expectation that feedback loops were present, for example: the operating temperature of a system influences the efficiency of collectors (and storage systems) whereas the efficiency in turn influences the operating temperature (delayed).

Implementing feedback loops in the models proved unnecessary during the research. Technical interactions and feedback loops are covered by the third party solar energy simulation tools that were found, and energy storage proved unnecessary due to the large demand. At that time, the development of the accounting model in Powersim was already largely underway and the decision was made to stick with it.

Powersim's ability to connect to MS. Excel, to perform Monte Carlo simulations and build-in optimization algorithms led me to choose it over other system dynamics packages such as VenSim[1]. These capabilities were very valuable during the research.

8.10 Chapter Summary

This chapter showed how different solar simulation tools were combined with a system dynamics model that was developed by the researcher. This toolbox will be used to estimate the performance of the solar energy with reasonable accuracy. The model structure and outcomes were validated when possible but some functions remain un-validated.

The purpose of this toolbox is to determine the performance of the four solar technologies that passed the screening tests when integrated with the production facility at Capua. Performance is measured by the key performance indicators that were defined by the Basis of Design.

An important insight that was gained during model development was that outcomes are sensitive to the electric efficiency of CHP systems. This led to a detailed investigation of the characteristics of available technologies, and subsequently to the realization that gas engines and steam turbines have higher electric efficiencies than steam turbines at the industrial scale. This benefit must be weighed against the problem that only steam turbines systems can be combined with solar heating. In fact, this realization led to the inclusion of CHP (as a non-solar alternative) in this research. This iteration was not reflected in this writing (except here) for reasons of clarity.

[1] An early prototype was made in VenSim

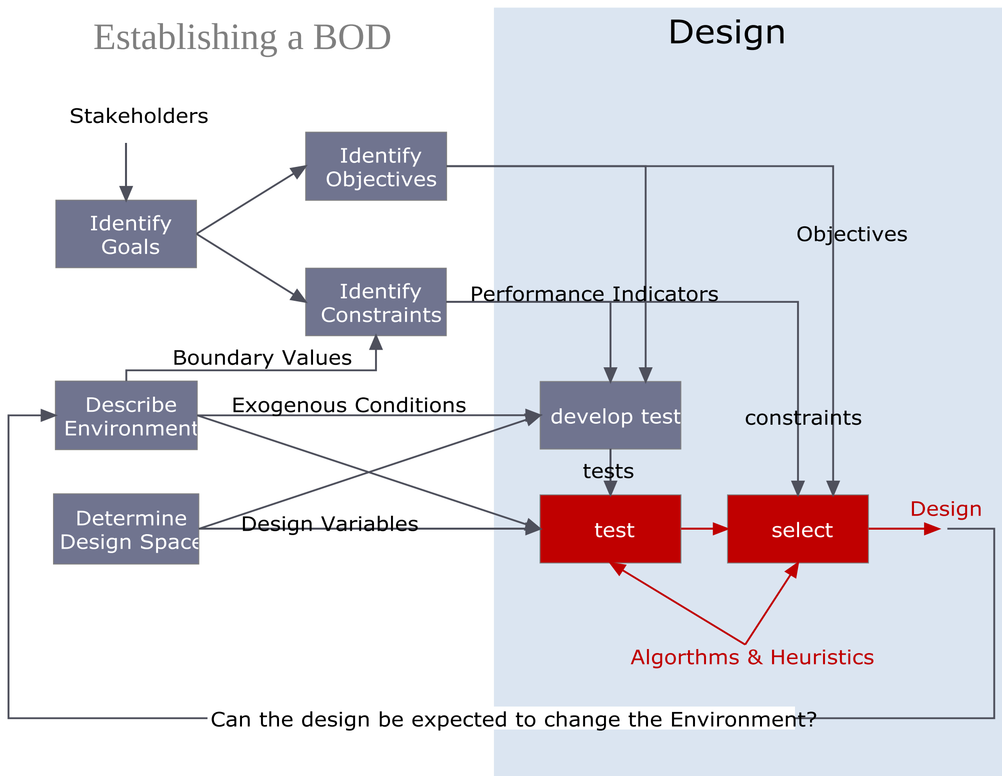
This chapter discussed the development of the toolbox; the next chapter is concerned with the actual simulation tests.

Chapter 9. Simulation Results & Project Selection

Research questions that will be addressed:

6. How do the selected solar design alternatives perform at Capua with respect to the objectives?

7. Which design alternative is most attractive for DSM Capua? (Including Business as Usual)



In this chapter the models that were developed and described in the previous chapter are used to predict the performance of the four design alternatives that passed the screening test. In order to do this one needs to make assumptions about the (future) environment the designs will operate in. Model results are quarantined from the researcher's interpretations as much as possible.

9.1 Model Input - Output Overview

MODEL INPUT	MODEL OUTPUT
General Input	
PV Electric Output	
PT Heat Output	
DSM Capua Electricity Demand (BAU)	**Key Performance Indicators**
DSM Capua Natural Gas Demand (BAU)	Initial Investment Costs
Electricity Price	Net Present Value
Natural Gas Price	Payback Period (deduced from CDCF graphs)
Inflation	
Risk factor (together discount factor)	CO_{2} reduction
Irradiation Uncertainty Factor	Electricity Consumption Reduction
Insurance costs as % of investment Costs	Natural Gas Consumption Reduction
Natural Gas Efficiency Improvements	
Electricity Efficiency Improvements	**Intermediate model output**
	Various Cashflows: (discounted / plain / cumulative)
Design Alternative Specific Input	
PV scale	gas costs
PT Scale	electricity costs
Full scale PV investment costs	Maintanance costs
Full Scale PT investment costs	Subsidies
Maximum % Boiler Assistence PT	Feedback income
CHP Scale	Insurance costs
CHP investment Costs per MW electric	CHP electricity output
CHP Electric Efficiency	CHP heat output
CHP Maintance costs per KWh (e)	CHP utilisation rate
	CHP Natural Gas Demand
Fixed Underlying Assuptions	NG Consumption displacement (by PT / CHP)
Efficiency of Italian Electriticity Grid	
CO_{2} emission per MWH Electrity produced on grid	PV Electricy production
	Electricity Discplacement / Export
Energy Content of Natural Gas	
Conto Energia fixed PV subsidies	
Feedback tarif is fraction of Electricity Price	

9.2 Model Input Values

Model input data is divided into g*eneral model input* and *design specific model input*. Design specific input are those settings that define the design alternatives, general input are all remaining factors.

General model input contains exogenous conditions and design specific input contains design variables. The exception is that investment cost is displayed under design specific input even though the designer has little control over the purchase price of these alternatives.

Often the input takes the form of a time series. For example to simulate heat and electricity demand a two year dataset is used in a loop over the simulation period.

General Model Input

Parameter	Distribution type	Values	Description
full scale PV Electric Output	Time series	See p 81	Full scale daily electric output as calculated by NREL SAM. Scaled down linearly based on PV Scale setting and influenced by irradiation uncertainty and PT efficiency uncertainty. One year data in a loop.
Full Scale PT Heat Output	Time series	See p 81	Full scale daily heat output of (Parabolic Troughs as calculated by NREL SAM). Scaled down linearly based on PT Scale and influenced by irradiation uncertainty. One year data in a loop.
DSM Capua Electricity Demand (BAU)	Time series	See p 50	The production site's total electricity import as measured in 2006 and 2007. Two year data in a loop.
DSM Capua Natural Gas Demand (BAU)	Time series	See p 50	The production site's total natural gas import as measured in 2006 and 2007. Two year data in a loop.
Electricity Price	Normal	EV = 110 Euro/MWh SD= 10 %	Constant electricity price fixed over time but picked randomly. Uncorrelated to natural gas price. EV based on 2006-2007 DSM Capua prices.
Natural Gas Price	Normal	EV = 0.37 Euro/m^3 SD=10 %	Constant natural gas price fixed over time but picked randomly. Uncorrelated to natural electricity Price. EV based on 2006-2007 DSM Capua prices.
Inflation	Uniform	2 - 4 %	Yearly devaluation of money (Inflation plus risk factor is the discount rate, which should be equal to the weighted average costs of capital WACC)
Risk factor	Uniform	5 -10 %	Factor that increases the discount rate due to the perceived risk of a project. In other words the premium that investors require given the risk of the investment.

Irradiation Uncertainty Factor	Uniform	90 -110 %	The power output by solar systems as imported from NREL SAM is multiplied by this random variable to investigate the effects of changing weather conditions or inaccuracies in the weather dataset. (It is also multiplied by the solar efficiency uncertainty factor.)
Insurance costs as % of investment Costs	Fixed	0.5%	yearly insurance costs as a percentage of total investment costs (regardless of system type)
Natural Gas Efficiency Improvements	Fixed	0%	Can be used to correct for pre-solar projects or expected efficiency improvement that reduce the BAU natural gas consumption.
Electricity Efficiency Improvements	Fixed	0%	Can be used to correct for pre-solar projects or expected efficiency improvement that reduce the BAU electricity consumption.
GHG emission due to electricity import from Italian grid	Fixed	0.6714 Kg/KWh	Carbon Dioxide Equivalents
GHG emission due to NG consumption	Fixed	1.78 Kg/m^3	Carbon Dioxide Equivalents
Energy Content of Natural Gas	Fixed	10.8 KWh/m^3	
PV feedback Price (subsidy)	Fixed	0.37 Euro/KWh	Fixed 20 year feedback tariff set by the Conto Energia subsidy scheme. (FOR PV ONLY)
Surplus **Feedback tariff**	Fixed	80% fraction of electricity Price	The model assumes that on-site produced electricity (not PV) can be sold and exported at a fraction of the import price at any point in time. CHP systems are heat-controlled. So even if the selling electricity price is high, the model continuous to reduce the CHP utilization rate when all heat demand is fulfilled.

Design Specific Model Settings

Parameter	Description	Unit	Photovoltaics	Parabolic Troughs – for preheating	Solar Assisted CHP	Gas Engine CHP
Scale (land area)	Occupied % of total land area at DSM Capua (65000 m^2)	%	10	20	10	
CHP Scale (total MW)	MW total Capacity Fuel input. Is equal to heat+electricity+losses ouput.	MW			5	6.5
Overall CHP effiency	% heat loss of total capacity	%			85-90	85-90
Electricity ratio	Ratio between electricity and heat output (electric efficiency or heat rate).	%			20-25	45-50
PT Investment costs	Investment costs for Parabolic Troughs on 100% of total land area. The model also uses a +/- 10% modifier. Includes all system costs.	M.Euro	15-16			
PV Investment Costs	Investment costs for flat plate photovoltaics. The model also uses a +/- 10% modifier. Includes all system costs.	M.Euro		31.5 38.5		
Gas Engine CHP Investment Costs	Investment costs of gas engine CHP. The model uses electric capacity to estimate investment costs because of data availability. (Electric capacity is calculated using scale, ratio and overall efficiency)	M.Euro /MW.elec		0.73 +-10%		
SA- CHP investment costs (excluding collectors)	Investment costs of steam turbine CHP. The model uses electric capacity to estimate investment costs because of data availability.	M.Euro /MW.elec			0.73 +-10%	

9.3 Simulation Results Summary

Table 15, Simulation Results Summary

		Investment	NPV[1]	PBP[2]	GHG red.	GHG red.
		M. Euro	*M. Euro*	*year*	*% of BAU*	*tCO_{2eq}/yr*
A	Flat Plate PV	3.5	0.5	12-19	1.6	602
B	Parabolic Trough Thermal	3.1	-1.5	NA	1.7	639
C	SA-CHP (5MW total)	3.3	1.6	8-25+[3]	26	9.776
D	CHP (6.5 MW total)	3.0	7.7	2.5-3.5	51	19.176

Table 15, Simulation Results Summary shows the expected performance of the four alternatives measured by the following KPI's:

- The required initial investment
- The Net Present Value for a 20 year lifetime
- The payback period in years (90% confidence interval)
- The Green House Gas emission reduction as a percentage of business as usual
- GHG emission reduction in Ton per year

The scale of the combined heat and power system (D) is optimized to result in the highest NPV. The other alternatives were scaled so that their investment costs were approximately 3 Million Euro's as well. This common factor makes it easier to compare the results.

Option A: Flat plate Photovoltaic's are subsidized via the "Conta Energia" and are expected to have a slightly positive NPV. Risk assessments however will show that the chances for negative results are quite high. It takes the alternative a long time to recover the investment costs: minimally 12 years. The green house gas reduction resulting from abating electricity consumption is

[1] Average result of Monte Carlo Simulations, 8-12% Weighted Average Cost of Capital (discount rate).

[2] 90% confidence interval

[3] 25+ means longer than life-span and simulation period

only 1.6% of total emissions.

Option B: Parabolic Troughs for heat, has a higher energy output than A, but in the form of less valuable heat. Additionally abating natural gas consumption is not subsidized. This results in the fact that this alternative is unable to recover investment costs and consequently has a negative NPV and a Pay Back Period that is longer than the projects lifetime.

Option C: Solar Assisted Combined Heat and Power, has a positive Net Present Value but more importantly results in much high emission reductions. The payback period is expected to be at least 8 years but is possibly higher than the 20 year simulation period, making the performance of this alternative quite unpredictable.

Option D: Combined Heat and Power, has the highest net present and achieves the highest emission reductions among the investigated alternatives. It also has the shortest expected payback period. It can achieve this performance because it is based on a direct combustion gas engine that has a higher electric efficiency than to the SA-CHP system that is based on a steam cycle.

9.4 Sensitivity Analysis

The summary of simulation results (Table 15, Simulation Results Summary) only shows the expected performance of the four technologies. This does not say anything about the uncertainty surrounding these results or the sensitivity to changing exogenous conditions[1]. Both are important to be able to interpret results and assess risk.

Scenario Analysis

This section continuous to first illustrate the sensitivity of economic performance to changing energy prices and the assumed discount factor. This is achieved by simulating the performance of the four technologies under three distinct scenarios and comparing the results.

Monte Carlo Analysis

Secondly this section presents the results of a Monte Carlo analysis. In essence the Monte Carlo simulation randomly generates many scenarios (based on the distributions defined in section 9.2) and calculates the performance of the alternative in each individual case. The results are then presented as a cone of uncertainty (using confidence intervals) surrounding the expected performance.

[1] Except the 90% confidence interval for PBP.

The Monte Carlo analysis includes more sources of uncertainty and is much more comprehensive than the scenario analysis. The scenario analysis on the other hand makes it much easier to illustrate <u>how</u> the different technologies are influenced differently by changes.

Scenario Analysis

Figure 33 explains how the results of the simulations will be displayed. The economic performance of a technology is calculated under each scenario and displayed over time (horizontal axis). At the simulation start-time the initial investment is made resulting in an immediate negative cash balance.

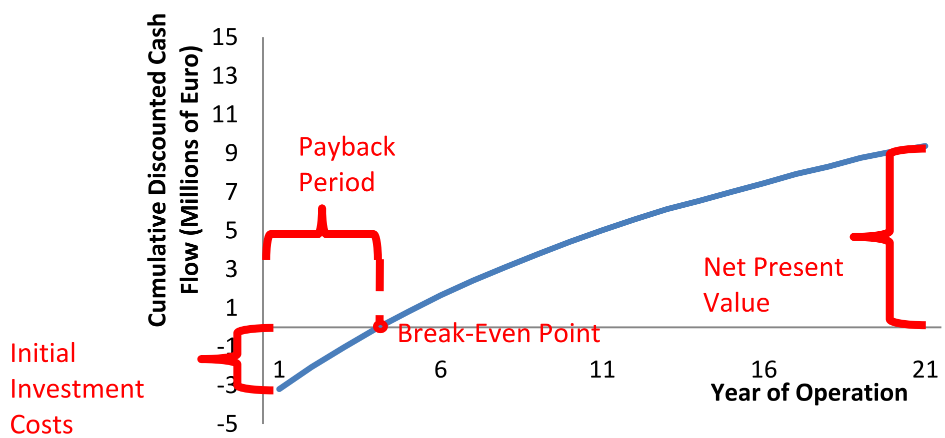


Figure 33, Explanatory Graph

The model assumes that the technology starts operation immediately after the investment is made and thus starts generating a cash inflow. This cash is discounted and added to the balance[1] displayed on the vertical axis. Over time the investment reaches a break-even point where the cumulative income surpasses the initial investment. The time required to reach this break-even point is defined as the payback period. The Net Present Value of the alternative (at t=0) is the cumulative value of all discounted future cash flows minus the initial investment. This is equal to the cumulative discounted cash balance at the end of the project's lifetime (assumed 20 years).

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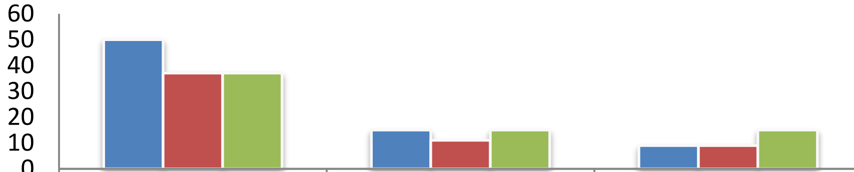
[1] To be precise: Cumulative Discounted Cash Flow. Note that this graph does not display the development of the NPV over time (the NPV of future cash flows diminishes over time if a project has a limited life-time as there are fewer and fewer future cash flows left). See for the difference between CDCF and NPV NPV vs. CDCF.

Three Scenarios



	Gas Price (EuroC/m^3)	Electricity Price (EuroC/Kwh)	WACC (%)
Scenario 1	50	15	9
Scenario 2	37	11	9
Scenario 3	37	15	15

Figure 34, Scenario definitions, ceteris paribus.

Figure 34 presents the three scenarios that are used. They differ in assumed energy prices (constant over time) and discount rate (weighed average cost of capital). Scenario 1 is a high energy price scenario. Scenario 2 can be regarded a base case scenario where energy prices are approximately equal to what was paid by DSM in previous years. And finally scenario 3 assumes considerably higher electricity prices but NG prices equal to Scenario 2, in addition it assumes a higher discount rate.

Scenario Analysis Results

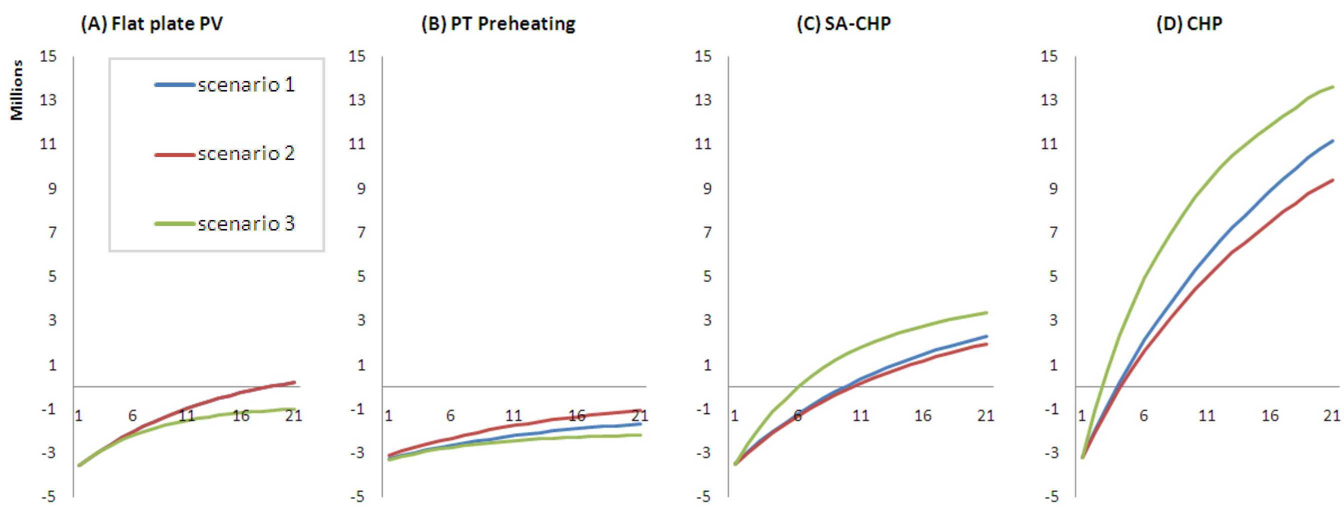


Figure 35, Scenario Analysis results, vert. axis = CDCF (Euros), hor.axis =time (years)

Figure 35 shows the performance of the four technologies under the circumstances defined by the three scenarios.

It can be seen that changing energy prices do not influence the performance of PV systems (A) because these generate income based on a fixed subsidy. Scenario 1&2 are therefore overlapping. The higher discount rate of scenario 3 results in a lower NPV, as can be expected.

Flat Plate PV

Parabolic Trough Preheating (B) for the industrial boilers reduces natural gas consumption. Its value therefore depends on the natural gas price but not on the electricity price. The net present value is negative under each scenario. It prevents about the same amount of green house gas emissions as PV technology but has a lower economic performance because it is not subsidized.

Parabolic Trough Preheating

Solar Assisted Combined Heat and Power (C) is influenced both by electricity as well as natural gas prices. A large spark spread (difference between electricity and NG prices) makes a CHP system more economic because it can produce expensive electricity by buying cheap NG. This is why this technology performs best under scenario 3, despite the higher discount rate. Equally interesting is that there is hardly any difference in economic performance under scenarios 1 and 2 although the energy prices in the first scenario are much higher. This is caused by the fact that the higher cost due to the consumption of natural gas are compensated for by the generation of more expensive electricity. This further illustrates that the performance of CHP systems is more sensitive to a varying spark spread than to overall increasing energy prices.

SA-CHP

The (gas engine) CHP system (D) has a higher electric efficiency than the SA-CHP system (C). Additionally it can be implemented at a larger scale at almost the same investment costs. Because electricity is more valuable than NG, the high efficiency results in a better economic performance. The graphs show a high sensitivity to the spark spread but not to overall increased energy prices. The scenario analysis does not include the fact that the gas engine CHP system is not sensitive to environmental conditions whereas the SA-CHP system is. This means that the economic performance is not only higher but probably also more predictable. The Monte Carlo analysis will include these effects.

Gas engine CHP

Monte Carlo Simulation

The results of the Monte Carlo simulation of the CHP (D) alternative are presented in this paragraph. The results of the other technologies can be found in Appendix F on page 146.

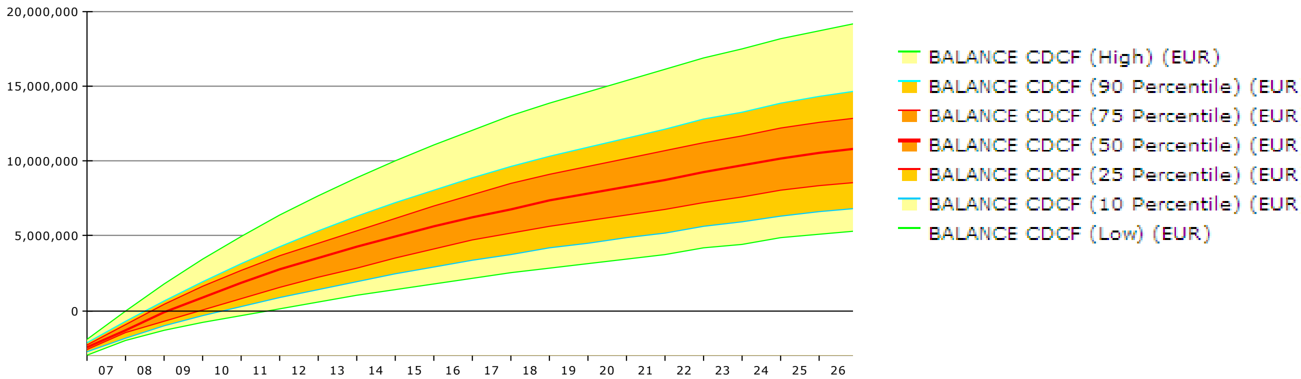


Figure 36, Results Monte Carlo Simulation CHP (D)

The graph shows that the NPV can vary significantly depending on the exogenous conditions. The lowest NPV found is about 5 M. Euros. In this situation, where all random values combine in the least favorable way, the payback period is about 4 years. This is still better than the best performance of the best solar alternative.

The relatively large spread in the results can partly be explained by the fact that the model assumes independent and uncorrelated natural gas and electricity prices. The prices of natural gas and electricity are in reality often strongly correlated. This is illustrated in Figure 37. This means that while overall energy prices may fluctuate, the difference between NG and electricity could remain relatively constant.

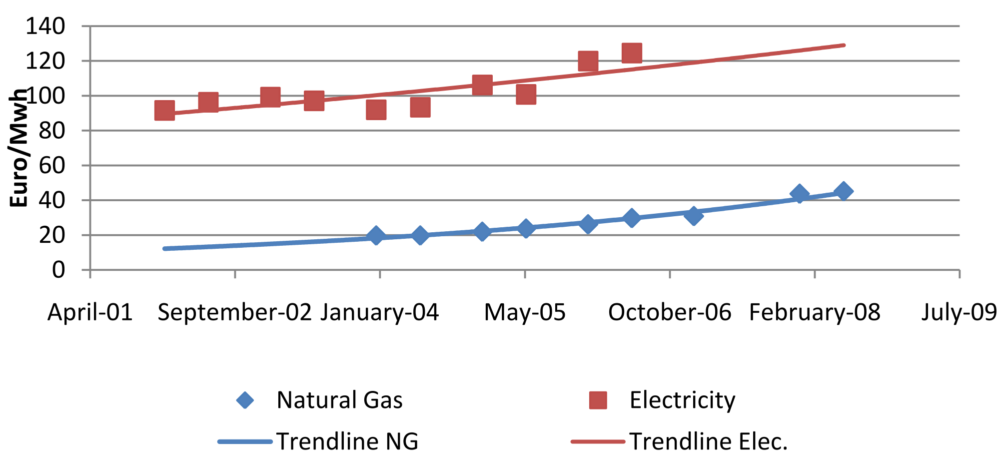


Figure 37, Development of Energy Prices for Industry, based on Eurostat data, price data from 2007 onwards was calculated by a renewed methodology, unfortunately many data points missing, exponential trend lines.

The scenario analysis illustrated that the CHP alternatives are much more sensitive to the spark spread and not so much to the overall energy prices.

Properly simulating correlating energy prices is difficult (and has not been attempted) but would probably result in a narrower "cone of uncertainty". This means that the investment might be less risky than can be concluded from this graph.

On the other hand, the energy prices in reality can vary greatly during the 20 project lifetime. The Monte Carlo simulations are based on energy prices that are constant over time and drawn from a normal distribution with a standard deviation of only 10% (of the expected value). This can result in an underestimation of risk. Nonetheless, uncertainty is greatest further in the future and the short payback period means that the initial investment is quickly recovered with the CHP alternative, whereas solar alternatives require much more time under the same conditions.

9.5 Project Selection

		Investment *M Euro*	**NPV** *M. Euro*	**PBP** *year*	**GHG red.** *% of BAU*
A	Flat Plate PV	3.5	0.5	12-19	1.6
B	Parabolic Trough Preheating	3.1	-1.5	NA	1.7
C	SA-CHP (5MW total)	3.3	1.6	8-25+	26
D	CHP (6.5 MW total)	3.0	10	2.5-3.5	51

Full PV system costs are substantial[1] (see Appendix H for cost buildup) and simulation results show that industrial application of PV systems is not attractive at Capua despite the Italian feedback subsidy (the Conto Energia). The simulation results also show that an investment in PV only has a limited impact on GHG emission reductions, as the volume of electricity produced is quite small compared to the facility's consumption rate.

Parabolic Trough systems can be installed at twice the area as PV systems at the same investment costs. However abating natural gas consumption is less valuable than electricity and is also not subsidized. The PT system cannot re-

[1] It seems that unrealistic expectations of PV systems can arise because mainstream media often report panel costs instead of system costs and peak capacity instead of actual energy output (which is location dependent but always and considerably lower).

cover the initial investment costs within the assumed 20 year lifetime. bon dioxide emission reductions are quite low compared to the required investment costs. The high minimum operating temperature and the low availability of direct normal radiation are clearly not favorable for a concentrating solar thermal system.

SA-CHP clearly performs better than the previous two solar alternatives. However this is mainly caused by the combined heat and power installation and not so much by the solar assistance.

When the assumption that the alternative MUST use solar radiation is ignored one realizes that a CHP system can be used that has an even better economic and ecological performance. A gas engine based CHP system can have a much higher electric efficiency than a steam cycle based SA-CHP system (at this industrial scale).Therefore it can generate more high value electricity at the cost of less valuable natural gas.

This also means that a CHP system can be implemented at a larger scale than a SA-CHP because it generates more electricity at the same amount of heat. Over-sizing would result in wasting heat, but could still be economically attractive. The utilization of waste heat and the high electric efficiency cause that the systems performs more effective than the Italian electricity grid and thereby reduces the carbon dioxide emissions caused by the DSM production facility. The reduction of GHG emissions can be as high as 50%. This is much higher than any of the other alternatives. The favorable ratio of heat and electricity demand of the DSM facility combined with the relatively high-electricity prices are very favorable for a gas engine based CHP system at Capua.

Selection of a project often involves making difficult trade-offs. Various researcher developed Multi Criteria Decision Analysis (MCDA) tools to assist. Variations of the Analytical Hierarchy Process (AHP) applied can often be found in solar literature, see for example (Elkarmi and Mustafa 1993; Ramanathan and Ganesh 1995; Chedid, Akiki et al. 1998; Akash, Mamlook et al. 1999; Ozgener and Hepbasli 2006; Chang, Wu et al. 2007; Aragones-Beltran, Chaparro-Gonzalez et al. 2010). Other approaches are also applied to solar energy decisions, for example fuzzy logic (Jaber, Jaber et al. 2006; Kaminaris, Tsoutsos et al. 2006). Or application of PROMETHEE (I/II) combined with GAIA[1] (Cavallaro 2009).

These MCDA tools can be very helpful when assessing other solar energy investments, hence the many references. In this particular case however the CHP system performs best on almost all the defined indicators (lowest investment costs, shortest payback period, highest NPV, highest GHG reduction) The only major trade-off required is that it is not a solar technology and that it is not modular, limiting flexibility.

9.6 Chapter Summary

This chapter presented the expected performance of the four technologies that passed the screening tests (PV, PT's for heat, SA-CHP, and CHP) when simulated using the toolbox that as developed in the previous chapter.

Performance was assessed under various circumstances, first via a scenario analysis and second via Monte Carlo simulations. From this the conclusion was drawn that the four technologies react differently to the environment. Scenario's that benefited one technology can be negative for another.

Nonetheless the performance of Combined Heat and Power systems is expected to be much better than the solar-only alternatives, both in economic and ecologic sense.

Modeling results indicate that the economic and ecologic performance of a gas-engine CHP system is much better than that of a steam turbine system. The higher electric efficiency of the former more than compensates for the inability to integrate solar panels, both in term of money as well as green house gas emissions. Given the objectives of DSM one must conclude that a gas-engine system outperforms solar energy systems under the conditions at Capua.

The only trade-offs that remain important are that this is not a solar technology and that it is not very modular. This led to the selection of Combined Heat and Power (not solar assisted) as the most appropriate technology among all that were investigated to be applied at DSM Capua.

[1] PROMETHEE (Preference Ranking Organisation METHod for Enrichment Evaluations) and GAIA (Graphical Analysis for Interactive Assistance)

Chapter 10. Corporate Solar Strategy

When it became clear that solar power at DSM Capua was not the best option to fulfill DSM's objectives the researcher started to focus on what could be done to increase the chances of DSM General implementing a solar energy project at an appropriate location. An additional research question was formulated:

How can the insights gained during this research be used to develop a corporate solar strategy?

10.1 Solar Strategy

Can the insights gained during this research also be used to formulate recommendations to DSM General? The answer can be both yes and no. No because the performance of solar energy systems is highly dependent on local conditions and generalization of results is difficult and unreliable. Yes because many key performance drivers were identified and this enables DSM General to develop and start a structured search for favorable conditions.

A complete revised solar strategy could not be developed during this study but three important points are made.

Firstly the researcher recommends that the site-by site investigation of solar power is replaced by a top down search for favorable locations, this because of the high sensitivity of solar systems to exogenous conditions and a facilities characteristics. This is discussed in section 10.2: location ranking.

Secondly, the researcher recommends that the investigation of solar investment opportunities becomes part of a standardized *integral energy analysis*. A solar strategy is merely a quest for implementing a particular technology whereas an integral energy analysis is a quest for fulfilling objectives. This analysis should not only contain the investigation of technical improvements but also for example contractual arrangements and energy acquisition strategies. This is discussed in section 10.3: Integral Energy Analysis.

Thirdly, before an investment decision is made additional investigation is required. First the project should be compared to other projects (including non-energy projects) that might be mutually exclusive due to limited funding. Funding strategies involving different ratio's between loans and equity are not discussed during this research but can have a considerable effect on the economic performance and risk from DSM's perspective. An additional option could be to use external investment funds that specifically target energy efficiency or RET investments at the costs of a percentage of the variable costs reduction. For example see (Tom Konrad 2009).

10.2 Process management

A top down approach by DSM General to investigate solar investment opportunities has benefits over site-by-site investigation. This top-down strategy should not be mistaken for a hierarchical structure where DSM General directly tells an individual site what to do once a favorable location is found. Although this might be possible, it is not necessarily a wise approach. There is information asymmetry and both parties need each other. Consciously designing the decision making process can help increase the chances of success.

De Bruijn, ten Heuvelhof and in 't Veld present four core elements to process design in their book Process Management (Bruijn, Veld et al. 2002):

Core elements of process design

- Openness
- Protection of Core Values
- Speed
- Substance

DSM General and DSM Capua were regarded different stakeholders in this research because they have different views on solar power. These different perspectives seem mainly based on their expectations about the distribution of risks and benefits within such a project. This is likely to occur within future projects as well. Benefits such as learning value are mainly valuable to DSM General regardless of direct consequences while investment risks are covered by the (partly) autonomous production location (that can also benefit from the direct decrease of fuel costs if all works out). The decision making process should be open and include all parties effected by the decision, otherwise resistance could form.

For successful implementation, it is important that the distribution of risks and benefits is acceptable to all parties. The core values of both parties should be protected. Depending on the degree of autonomy of the individual production locations, various constructions are possible to distribute risk. For example, agreements can be made to rule out resignations, share investment costs, price risks, unexpected costs, or even variable costs reductions

The protection of core values of both parties also removes barriers to information sharing, and facilitates further openness of the decision making process. To further increase the chances of success and speed up the process it could be wise to a-priory agree to contact external experts in the case of uncertainty about facts (and negotiated knowledge) and make sure that all parties have the power to commit to the decisions they make.

10.3 Location Ranking

A revised strategy including a top-down and structured search for favorable locations is discussed. The identification of key performance drivers and the analysis tool that was developed during this study can aid in assessing and ranking locations.

It seems that solar energy for industrial application can be economically and ecologically attractive, but only under very favorable conditions. This research concludes that the conditions at DSM Capua are not favorable (enough) for solar energy. Instead of choosing a site and then investigating solar energy this research recommends adopting a different approach: a structured search for favorable conditions and ranking DSM production locations, after which research effort can be directed to the top locations. Subsequent research is needed in order to define a proper ranking and assessment method but many important Key Performance Drives were already identified.

Low temperature heat collection system systems (and hybrids) such as solar ponds and flat plates, are not applicable at Capua. These systems where therefore not modeled in detail. However it is important to note that is the case only because there is no low temperature heat demand (<100C) at the site (due to the utilization of waste heat from the air compressors). In general low temperature systems have lower investment costs and when considering solar energy investments at other locations it would be wise to specifically search for opportunities to provide low temperature process heat or to pre-heat boiler water. Unfortunately the toolbox used during this study was never developed to simulate low temperature solar systems as these were not applicable at Capua.

High availability of beam radiation is important but less so if the temperature of demand remains low (then scattered radiation might be sufficient). The production location preferably already has an efficient steam based CHP system into which solar preheating can be integrated. Thereby the solar energy system abates electricity consumption which is often more valuable than heat / natural gas. High energy prices increase the chance of a solar energy system, but a large spark-spread is more important when considering combined heat and power. Subsequent research is needed in order to define a proper ranking and assessment method but the factors that the researcher suspects are most important, are:

- Low temperature, high volume heat demand
- High availability of direct beam radiation (and small seasonal variations)
- High Fossil Fuel Prices
- Subsidies (fixed, mandatory feedback tariffs, tax reductions, CO_2 trading, etc)
- Low risk of damage (due to extreme weather for example)

An extensive list of Key Performance Drivers can be found in Table 4, KPD's and Effects.

Figure 31 and 32 show the availability of direct normal radiation and global radiation[1]. Although yearly averages are only a very rough indicator, the figures were used to illustrate potentially interesting locations for implementing solar energy. Red circles on figure 1 are used to mark locations where solar might be interesting to provide heat below 100°C. Figure 2 on the other hand shows locations where concentrating technologies might be applied to yield higher temperatures.

The figures illustrate that the inability of concentrating solar systems to utilize anything other than direct beam radiation has wide consequences for both the applicability of solar energy at Capua as well as for DSM General's solar strategy.

[1] Beam radiation comes directly from the direction of the sun, global radiation might be scattered by the atmosphere / clouds.

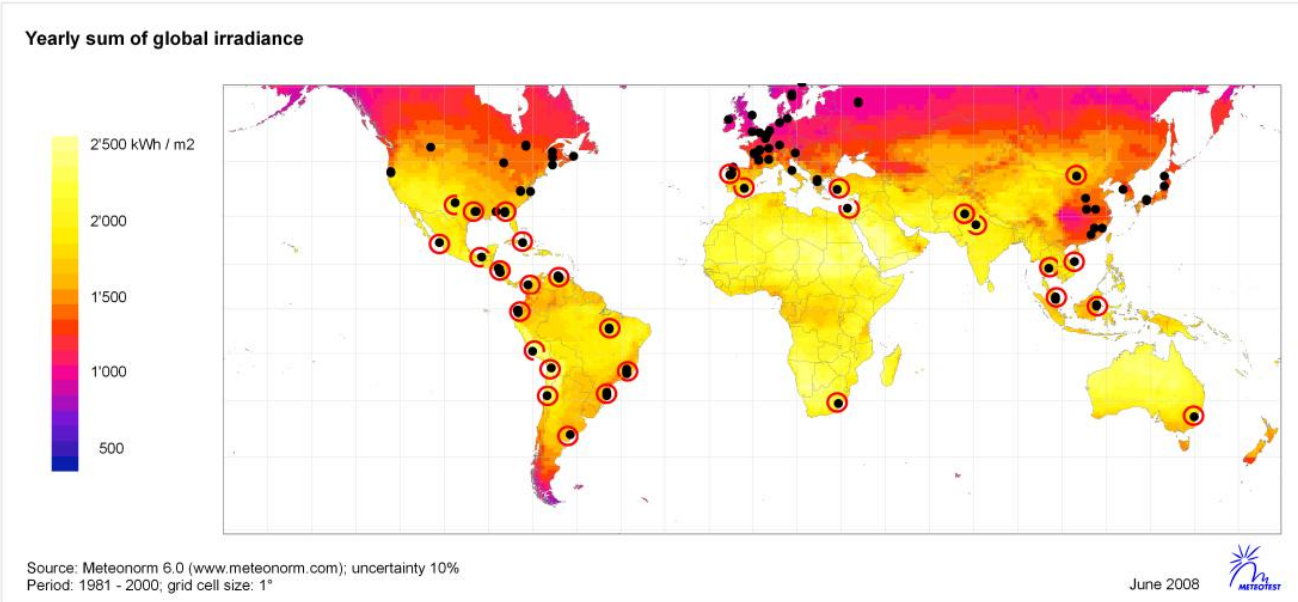


Figure 39, Global radiation map (meteonorm) with DSM production locations marked

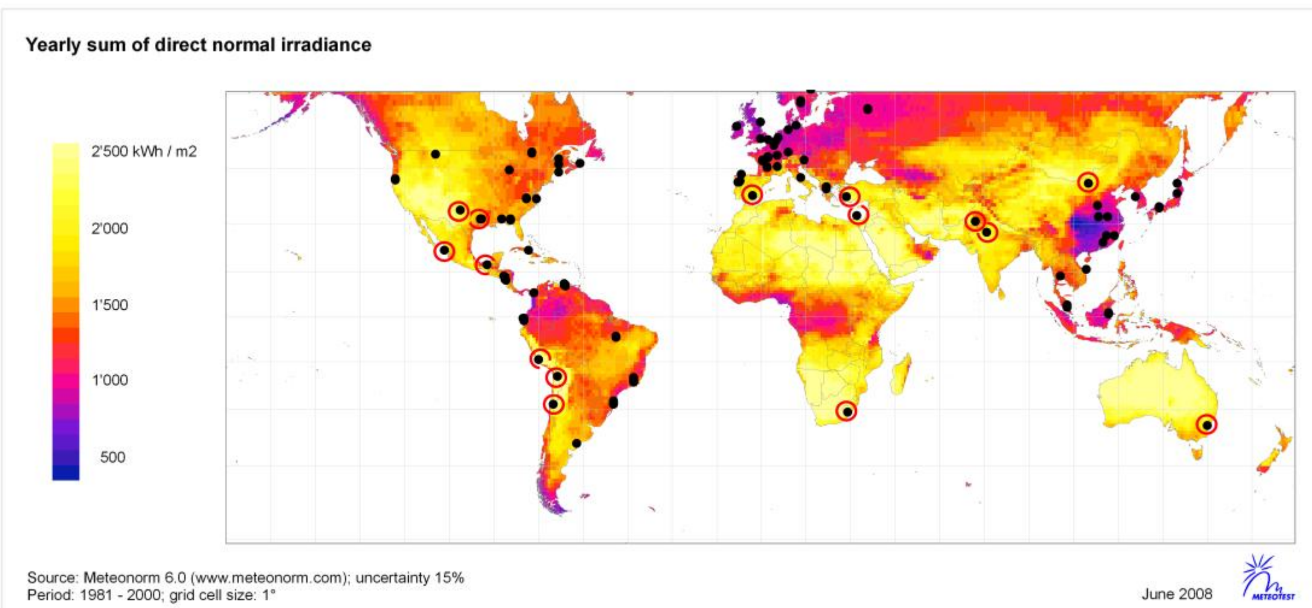


Figure 38, direct normal radiation map (meteonorm) with DSM production locations marked

10.4 Integral Energy Analysis

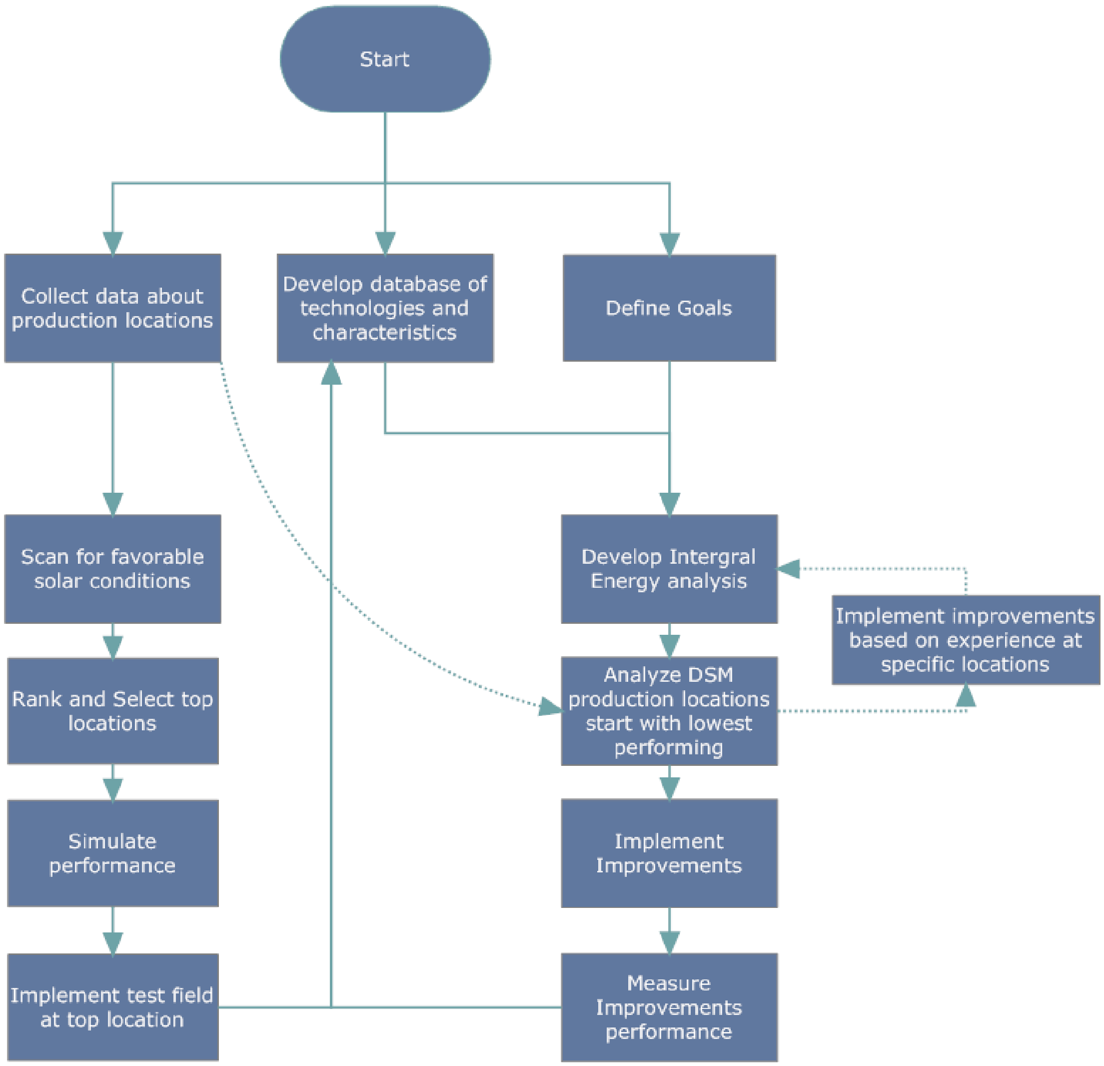


Figure 40, possible integration of solar strategy in broader analysis.

Efficiency improvements

Many of DSM's production locations are based on fermentation technology. The similarity of production locations makes that it could be beneficial to invest in centralized research to optimize the energy efficiency of this process. Especially technologies allowing simultaneous production of electricity, heat, cold and work (air compression) for example developed by SOPOGY[1], could possibly integrate well with the fermentation production process (SOPOGY

[1] SOPOGY is a company that also manufactures solar systems!

2009). Thorough analysis of this technology fell outside the scope of this particular research, but is an interesting subject for future investigation.

It does not make much sense to produce energy via solar power when that energy use could have been avoided in the first place. It is unlikely that in the medium term it becomes more expensive to improve energy efficiency than it would be to simply install some more solar panels. The same holds for other renewable energy sources. Some researchers on the other hand argue that the beneficial effects of efficiency improvements are to a large extend cancelled out by a decrease of fuel prices that in turns causes a consumption increase somewhere else.

When investigating individual locations for solar power it is important to first consider efficiency improvements and/or spot market operation. This because a change in the net energy demand or prices has an effect on the economic (and ecologic) performance of the solar energy investment.

Periodically reassess and compare energy acquisition strategies

A large portion of DSM Capua's variable costs are caused by natural gas and electricity import. Apart from decreasing the import volume it might sometimes be possible to reduce price. This, however, often requires a change in strategy. An option for facilities of sufficient size is to operate on electricity spot markets (IPEX in Italy). Operating on such markets requires expertise and manpower. Depending on the consumption pattern over time it is possible that spot market prices are more favorable than bilateral contracts with energy suppliers or intermediaries. Nonetheless, the possibility of lower energy costs needs to be balanced against the higher price risk.

In many circumstances the timing and pattern of consumption is essential. This is because electricity spot prices can vary greatly over time due to the impossibility to store electricity combined with large variations in total demand. The researcher recommends that the difference between local spot markets and bilateral contracts is closely monitored for large DSM sites, and additionally suggests that the energy acquisition strategies and payoffs of these sites are compared on a corporate level.

Perform standardized measurements of energy use of production facilities, subsystems and improvement projects throughout the company

Measuring the performance of plants throughout the company enables DSM to use energy benchmarking. Benchmarking can both be an important tool for discovering opportunities for improvement but is also likely to be a strong motivation for employees. Another important aspect is that designing and selecting between technical solutions is often done with the help of models. Models help to predict the performance of alternatives and these models can be much improved if up-to-date and standardized information about performance and energy consumption rate is available. Especially when investments in innovative systems such as solar energy are made this research recommends measuring and logging performance of these systems as well. This could be beneficial for predicting the performance on other locations. It might also be worthwhile to install non-operational (identical) solar panels at different DSM locations only to compare performance. This makes it easier to identify top locations, and validate and improve solar calculations. The costs of this could be compensated for by selecting a proper location for a full size solar project.

Actively keeping track of a changing environment in terms of technologic development and energy prices is important for similar reasons. New technologies (both solar and non-solar) could become very interesting for DSM production locations.

10.5 Chapter Summary

When it became clear that solar power at DSM Capua was not the best option to fulfill DSM's objectives the researcher started to focus on what could be done to increase the chances of DSM implementing a solar energy project at an appropriate location. This resulted in a recommendation for developing a corporate solar energy strategy.

Many key performance drivers were identified and this enables DSM General to develop and start a top-down structured search for favorable conditions. Still detailed analysis would be required but the researcher believes that the chances of success become much higher now one exactly knows what to look for.

In addition, the researcher recommends that the investigation of solar investment opportunities should become part of an integral energy analysis. That should include conventional as well as renewable energy technology assessments. More importantly, it should start with energy efficiency improvements and can include non-technical aspects such as alternative energy acquisition strategies.

PART IV Conclusions and Recommendations

Chapter 11. Conclusions

11.1 General Conclusion

The technical performance of any solar energy technology implemented at a specific location cannot easily be predicted. Energy output is dependent on local conditions and small variations in circumstances can have a large influence on system performance. This research was aimed designing a solar energy system, retrofitted to the existing production system at DSM Capua (Italy) and assessing the technological, economical and ecological performance of this investment. The main research question was formulated as:

How can Royal DSM improve its environmental footprint through investment in solar energy at its facility in Capua, Italy?

The main research results and the answer to this question can be summarized as follows:

Solar Assisted Combined Heat and Power: best solar alternative but not recommended.

DSM can improve its environmental footprint by investing in a solar assisted Combined Heat and Power (CHP) system at Capua. This, on parabolic-troughs based design, that simultaneously delivers electricity and process heat, proved best among many investigated solar technologies. Nonetheless, its expected performance is disappointing and investment is not advised.

A gas-engine CHP is more suitable at DSM Capua.

Instead, a gas-engine CHP system is highly recommended. This technology performs very well with respect to DSM Capua's objectives but cannot be combined with solar pre-heating. It is expected to result in approximately 50% green house gas emission reduction and has a short payback period (2.5-3.5 years). All investments involve risk but it is important to note that this investment can also be seen as an insurance policy that secures against the risks of energy price volatility. Systems that simultaneously produce electricity, heat, work (for air compression) and cold, are possible even more attractive but were not investigated in details

A top down strategy is advised to search for favorable solar locations.

This research suggests that industrial solar energy can be interesting at other DSM locations where conditions are more favorable. Learning value of a pilot project hardly depends on the location. A revised strategy that includes a top-down and structured search for favorable locations is therefore recommended. The identification of key performance drivers and the analysis toolbox that was developed during this study can aid in assessing and ranking locations. Favorable conditions that DSM Capua lacks include: low temperature heat demand and high availability of direct beam radiation.

Industrial locations with a low temperature heat demand (<100 ^oC) are probably more suitable for retrofitting a solar energy system than DSM Capua. Unfortunately the toolbox used to asses DSM Capua was not developed to analyze the performance of low-temperature solar technologies such as evacuated tubes. Adding this ability will probably require an investment in a commercial solar analysis product.

The developed toolbox needs extensions to include low-temp technologies.

Last but not least this research recommends that the investigation of solar investment opportunities becomes part of an integral energy analysis. This analysis should at least include the investigation of energy efficiency improvements because abating energy consumption is generally more cost-effective than implementing renewable energy sources. A solar strategy is merely a quest for implementing a particular technology whereas an integral energy analysis is a quest for fulfilling objectives.

The solar strategy should become part of an integral energy analysis.

When it became clear that solar power at DSM Capua was not the best option to fulfill DSM's objectives the researcher started to focus on what could be done to increase the chances of DSM implementing a solar energy project at an appropriate location. This resulted in a recommendation for changing the corporate solar energy strategy. Consequently, a differentiation was made between research conclusions with respect to DSM Capua and at DSM General; these will now be elaborated upon.

11.2 DSM Capua

Photovoltaic technologies proved ecologically and economically unattractive at Capua. The combination of a high temperature heat demand and a limited amount of direct beam radiation at Capua caused a disappointing performance of thermal solar systems as well.

The investigation of *Solar Assisted Combined and Heat and Power* systems led to the conclusion that a gas-engine system is the best CHP choice at DSM Capua. This technology however cannot be combined with solar pre-heating as there is no water to pre-heat.

The DSM Capua production facility proved a very interesting location for a Combined Heat and Power (CHP) system. The physical proximity of, and ratio between, electricity and heat demand are suitable for a CHP system. The high electric efficiency of a gas engine means that even without heat recovery this system could outperform the Italian electricity grid. High efficiency combined with “waste” heat utilization cause substantial reduction in both variable energy costs as well as carbon dioxide emissions. This results in a 2.5 to 3.5 year payback period and up to 50% carbon dioxide emissions reductions. These impressive figures are currently far beyond the reach of solar energy technology.

Before an investment decision is made additional investigation is required. First the project should be compared to other projects (including non-energy projects) that might be mutually exclusive due to limited funding. Funding strategies involving different ratio’s between loans and equity are not discussed during this research but can have a considerable effect on the economic performance and risk from DSM’s perspective. An additional option could be to use external investment funds that specifically target energy efficiency or RET investments at the costs of a percentage of the variable costs reduction. For example see (Tom Konrad 2009).

Secondly, the optimal scale of investment should be reconsidered when new projections about the future production of the DSM site are made.

It is important to note that an investment in CHP can reduce price risk. The investment can be seen as an insurance policy where a fixed investment reduces dependence on exogenous conditions, in this case energy prices. The predictability of the economic performance of the facility as a whole can therefore improve once the investment is made. The risk of never recovering sunk costs is low due to the short payback period.

11.3 DSM General

Can the insights gained during this research also be used to formulate recommendations to DSM General? The answer can be both yes and no.

No, because the performance of solar energy systems is highly dependent on local conditions and generalization of results is difficult and unreliable.

Yes, because many key performance drivers were identified and this enables DSM General to develop and start a structured search for favorable conditions. Still detailed analysis would be required but the researcher believes that the chances of success become much higher now one exactly knows what to look for.

One needs to look for a production facility that has a high demand for low temperature heat. High availability of beam radiation is always important but less so if the temperature of demand remains low (then scattered radiation might be sufficient). The production location preferably already has an efficient steam based CHP system into which solar preheating can be integrated. Thereby the solar energy system abates electricity consumption which is more valuable than natural gas.

High energy prices increase the chance of a solar energy system. But a large spark-spread is more important when considering combined heat and power. The site-by site investigation should be replaced by a structured search for DSM locations where the conditions with respect to these factors are favorable.

Subsequent research is needed in order to define a proper ranking and assessment method but the factors that this research deemed most important are:

- Low temperature, high volume heat demand
- High availability of direct beam radiation (and small seasonal variations)
- High Fossil Fuel Prices
- Subsidies (fixed, mandatory feedback tariffs, tax reductions, CO_2 trading, etc)

The analysis tool developed during this study can be used to help find and investigate top locations. The model is able to use data about the energy output of a solar energy system over time (heat and/or electricity) as input (among others) and calculate more important performance indicators, such as NPV, GHG emission reductions, abated fossil fuel consumption, investment costs etc. The model is able to cope with different energy price scenarios, subsidy schemes, feedback tariffs, discount rates, scales of implementation, efficiency improvements, grid efficiencies, etc. It also includes the simulation of various CHP systems onto which solar heat can be connected. It can perform risk assessments by calculating (and graphing) confidence intervals based on stochastic assumptions and it can additionally use evolutionary optimization algorithms to calculate the optimal scale of an investment (if there is an optimum).

Last but not least it is the researcher's opinion that the investigation of solar investment opportunities should become part of an integral energy analysis. A solar strategy is merely a quest for implementing a particular technology whereas an integral energy analysis is a quest for fulfilling objectives.

Chapter 12. Recommendations

12.1 Recommendations towards DSM Capua

DSM should not invest in Solar Power at Capua at this time

After investigation of many solar alternatives the researcher must conclude that the implementation of a solar technology at Capua does not serve DSM's objectives. There are three main considerations that led to this recommendation:

First; a Combined Heat and Power system would have a much better economical and ecological performance at Capua than any of the solar alternatives.

Second; both the weather conditions as well as the facility's energy demand characteristics are not favorable for implementation of a solar power system.

Third; the value of learning from a pilot project will not diminish if a more suitable location is chosen but disappointing performance at Capua could very well inhibit future implementation of other solar projects.

DSM should consider an Investment in Combined Heat and Power

The combination of relatively high energy prices, a large demand for heat and electricity (in a favorable ratio) and the high electric efficiency certain CHP systems, make that an investment in such a system has an expected 2.5-3.5 year payback period. The high electric efficiency and the utilization of "waste heat" cause that implementation of a CHP system can result in substantially lower green house gas emissions than does importing electricity and natural gas separately. Simulations indicate that reductions up to 50% compared to business as usual are possible. This is <u>much</u> more than any solar technology can currently accomplish within reasonable economic constraints.

It is important to note that the reason why the recommendation states*: consider an investment in CHP*, rather than: *Invest in CHP*, is because an investment decision depends on factors that lie outside the scope of this research. The investment decision does not depend on the characteristics of this CHP project alone, but on how it relates to other investment proposals. Limited funds cause that technically unrelated projects can become mutually exclusive. In addition this research did not include investigation of some factors that could be important, such as sales projections.

DSM should investigate the possibility to reduce the boiler temperature and pressure

The DSM production facility in Capua use to have a demand for steam at higher temperatures and pressure than is currently required. The boiler is however still operating at the higher temperature, and reduction valves are used to limit pressure. This is necessary to avoid damaging various components during sterilization. Replacing the reduction valves with less rigorous ones and lowering boiler temperature saves natural gas consumption. Lowering boiler temperature does require investigation into regulations guarding contamination risks, but could be well worthwhile.

DSM should be cautious when analyzing the investment risk of energy projects.

All Investments involve risk because future returns are uncertain by definition. During this research the returns of solar energy projects were calculated as the value of the fuels that would have been consumed if the investment was not made.

This approach might lead to the conclusion that an energy project is risky because of fluctuating energy prices. According to this line of reasoning investing in a project increases risk because money is spent but returns remain uncertain.

However if one considerers the facility as a whole with and without an energy investment one can reach the opposite conclusion. An energy investment can make the facility as a whole less dependent on energy price fluctuations simply by lowering net energy consumption. The investment can reduce risk because it makes the future returns of the facility as a whole less uncertain[1] compared to business as usual regardless of future price developments[2] Such an investment can therefore be compared to an insurance policy where future net returns are made less volatile at the costs of a fixed investment.

Lastly it should be noted that the model used in this research does not correct for the fact that a higher annual demand for natural gas and/or electricity often can result in lower prices, and vice versa. Suppliers offer better deals

[1] Less uncertain performance means more predictable, not nesserily better!

[2] In addition: once the investment is made the variable costs of production decline and therefore DSM Capua can more easily compete for production contracts. Thereby again decreasing investment risk compared to business as usual.

when the buyer consumes larger quantities.

12.2 Recommendations towards DSM General

DSM should adopt a top-down strategy for locating favorable solar locations.

Solar energy systems are dependent on many exogenous conditions. A top down search for favorable locations can be much more effective then site by site investigation. Developing a ranking method however might prove difficult and could require substantial investigation.

One needs to look for a production facility that has a high demand for low temperature heat. High availability of beam radiation is always important but less so if the temperature of demand remains low (then scattered radiation might be sufficient). The production location preferably already has an efficient steam based CHP system into which solar preheating can be integrated. Thereby the solar energy system abates electricity consumption which is more valuable than natural gas.

DSM should incorporate solar strategy within an integral energy analysis.

This research recommends that the investigation of solar investment opportunities becomes part of an integral energy analysis. A solar strategy is merely a quest for implementing a particular technology whereas an integral energy analysis is a quest for fulfilling objectives

Energy efficiency improvements should be considered before solar energy investments.

The integral energy analysis should at least include the investigation of energy efficiency improvements because abating energy consumption is generally more cost-effective than implementing renewable energy sources.

DSM should consider using standardized methods and scenarios for increased transparency of renewable energy investment studies.

Broad use of pre-defined scenarios can help making investment studies for various locations and projects more transparent and more easily comparable.

DSM should investigate price developments in energy spot markets versus bilateral contracts.

The strategy for buying energy can have a large effect on prices and risks. The difference between local spot market prices and local bilateral contracts can be substantial. The time-dependent production of RET technologies influences the choice between spot market and contracts. For example, electricity prices on spot markets are often high at noon during summermoths due to air-conditioning induced peak demand. At the same time solar systems produce maximally. This research recommends that the difference between spot market prices and bilateral contracts of local facilities is benchmarked on a corporate level.

12.3 Future Research

Development of solar energy decision support system for industrial use

The scientific value of the developed toolbox is rather limited because it is too specific for DSM and did only use tools that are freely available. Important however was the inclusion of institutional and economic factors into the analysis. Additionally the researcher found that tools to assess the performance of a solar technology WHEN INTEGRATED WITH AN INDUSTRIAL PROCESS are hardly available. A tool such as TRNSYS is flexible enough to be able to simulate performance but this is complicated, requires time and a lot of expertise. Developing, or extending, a frond-end such as NREL-SAM, to include industrial application might lower the barrier for companies (especially small &medium size) to seriously start investigating solar power.

Life Cycle Assessment

This research did not perform a life cycle assessment of any of the solar power systems. The use of resources to develop, build, maintain, demolish and recycle the alternatives was thus not assessed. A LCA would give a more accurate prediction of the impact of the design alternatives but will require considerable research time. Therefore, it is recommended that LCA is only applied after screening procedures.

Location ranking

Developing a method for ranking industrial locations before focusing research efforts to the most interesting ones can increase the chances of successfully implementing solar energy (and other RET). This research resulted in the identification of key performance drivers but did not result in a fully developed ranking system. Developing such a ranking system is a difficult task because solar technologies react differently to exogenous conditions.

Chapter 13. Reflection

In this final chapter, I would like to reflect on the research results and process. This is done from three different perspectives. First I would like discuss the value of this research for the main stakeholders; DSM Capua and DSM General. The scientific value of this research will be discussed next, and finally I will reflect on the graduation process from a personal perspective.

13.1 Research Value for Direct Stakeholders

Was the researcher able to find a satisfactory answer to the main research question?

This research concluded that implementing solar energy at Capua is not in the best interest of DSM given its objectives. This answer is valuable but somewhat disappointing for those at DSM who try to improve the environmental impact of industrial processes via solar energy technology within reasonable economic boundaries.

Once the research came to this conclusion, Laurens de Vries, one of my supervisors told me to remember that at the end of this research it is unlikely that anyone will still be interested in the original research question. Instead, stakeholders are interested in the value of all the insights that resulted from the research regardless of its initial goal. I started to focus on two other questions:

- First, what can be done at DSM Capua to achieve their economic and ecological objectives?
- Secondly, can the insights gained during the case study be used to improve the chances of successfully implementing solar energy at another DSM location?

This resulted in proposal for a CHP-system that can help DSM Capua achieve its goals, and a starting point for the development of corporate solar strategy. Additionally the toolbox can be of value for follow-up research.

Despite the fact that there is room for improvement, the research thus certainly resulted in specific insights that are of interest for DSM Capua and DSM General. Recommended insights to tackle limitations of the research with respect to its value for DSM are:

Research limitations

- Further refinement and development of the simulation toolbox is necessary to include solar technologies that were not applicable at DSM Capua but can be very interesting at other locations (such as evacuated tubes collectors) and to simulate performance under the conditions at other locations. In fact, if another student-researcher continues this research I recommend to rebuild the toolbox while paying more attention to software modularity and flexibility.

- Tax regulation and financing options can have an important effect on the economics of a solar power project but these were regarded outside the research scope.
- Making a decision between design alternatives for improving the energy system of an industrial facility often involves making trade-offs. Multi Criteria Decision Analysis (MCDA) methods specifically designed for solar power by other researchers were not necessary nor discussed during this research, but can prove vital at other locations.

13.2 Research Value for Scientific Community

I suspect that the direct value of this research for the scientific community[1] is somewhat limited. The research was primarily of a pragmatic nature and the initial research results are quite specific to DSM Capua. Nonetheless some important insight have been gained that could benefit future research.

At the start of this research, I set out to make an incremental contribution to scientific knowledge by applying real options theory to help evaluate the economic performance of solar energy investments. To my knowledge, this has not been attempted before. Solar technology is often characterized by a high degree of modularity. Modularity is a source of flexibility (the ability to take actions in a changing environment) and conventional valuation methodologies such as discounted cash-flow techniques (NPV, IRR, ROI) fail to recognize and account for the value of this flexibility. Real Options Analysis (ROA), can in such cases, be used to predict a more appropriate project value.

Applying ROA however can be a difficult and time consuming process that is mainly valuable when methods such as NPV are insufficient to clarify the investment decision. In this particular case the economic performance of the design alternatives was so far apart that achieving a higher accuracy of economic predictions was unnecessary for project selection. This led to the

[1] This formulation avoids the term "scientific value" in a weak attempt to avoid the philosophical discussion about what exactly constitutes scientific value, for more information on this subject see Bergström, L. (1996) "Scientific Value." International Studies in the Philosophy of Science **10**, 189-202. http://www.philosophy.su.se/texter/scientificvalue.htm

decision to abandon ROA methods altogether, which in turn led to the question: is there an alternative way for me to contribute to scientific knowledge?

The toolbox that was developed during this study is also of limited scientific value, partly because it is exclusively based on programs that were freely available to me and at the same time do not require a level of expertise that I do no posses. Nonetheless, the main scientific value of this research is related to the development of this toolbox.

In my opinion, the main contribution of this research was the structured incorporation of non-technical factors in the analysis of industrial solar energy systems, the identification of key performance drivers, a system boundary that incorporates the local grid characteristics and the translation of technical performance data into key performance indicators that are important to commercial investors. I hope that these findings can benefit and inspire researchers to develop or extend tools such as NREL-SAM to include industrial solar energy systems. This could lower the barrier for industrial companies to start investigating their solar energy investment opportunities.

Additionally I hope that my extensions of the *meta-model of design* can be of use to other students at the TPM faculty, where the original is frequently used during design-oriented projects.

13.3 Personal Reflection

I started my academic schooling as a student of mechanical engineering. After one year I made the decision to switch to the faculty of technology, policy and management (TPM). I found the focus on technology at mechanical engineering to narrow to my liking. My fear that that the bird's eye view of TPM would come at the price of knowing too little about almost everything proved ungrounded. The freedom that one has at TPM to steer oneself towards pragmatic or abstract projects, while encountering both, was very satisfying. This graduation project made me realize that I must have learned a lot during the previous years, and also that there is much more to learn.

What would the researcher have done differently with the wisdom of hindsight?

As stated before: the process of graduation unfortunately did not coincide with the easiest period of my life. Partly due to these circumstances, I at times failed to make deadlines on time. Instead of communicating this with DSM and supervisors, I tried to make up for it before the next deadline, which then, in turn, proved impossible. This, I feel, created a downwards spiral during the middle of the research, after I returned from Italy. This barrier was only overcome after people at DSM realized that something was out of place, confronted me with it, and helped me back on track. With the wisdom of hindsight, I wish I had communicated more pro-actively during this period, this could have prevented lot of stress and would have been more professional towards DSM.

The opportunity to graduate at such a highly respected company as Royal DSM, involving an extremely important and interesting subject such as renewable energy, while visiting such a beautiful country as Italy, seemed almost too good to be true. In the end, I can say it was a lot of work, a lot of fun, and a great experience.

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Appendix A. Technology Capital Cost Comparison

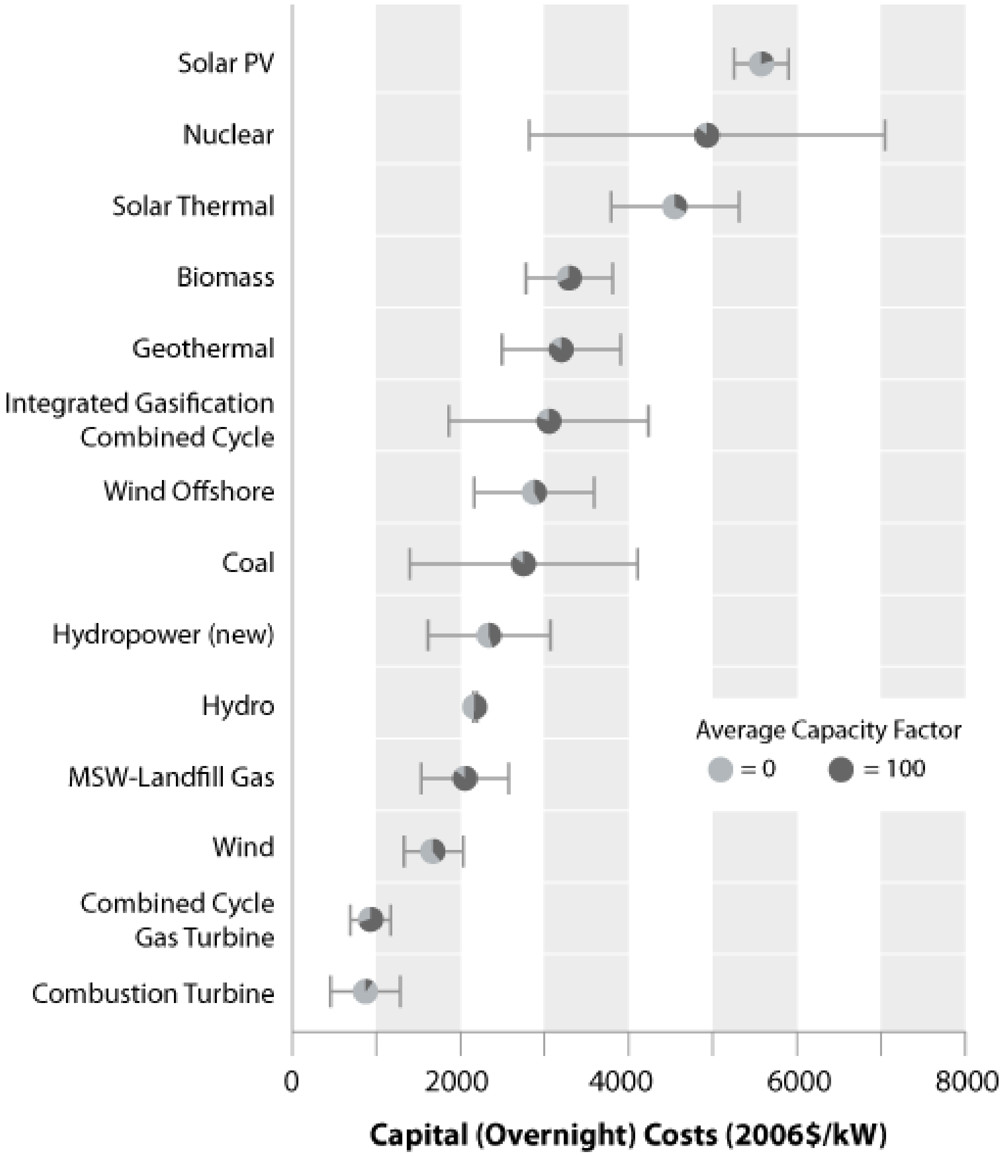


Figure 41, Capital Costs Ranges (1 standard deviation left & right) of various technologies at USA (NREL 2009)

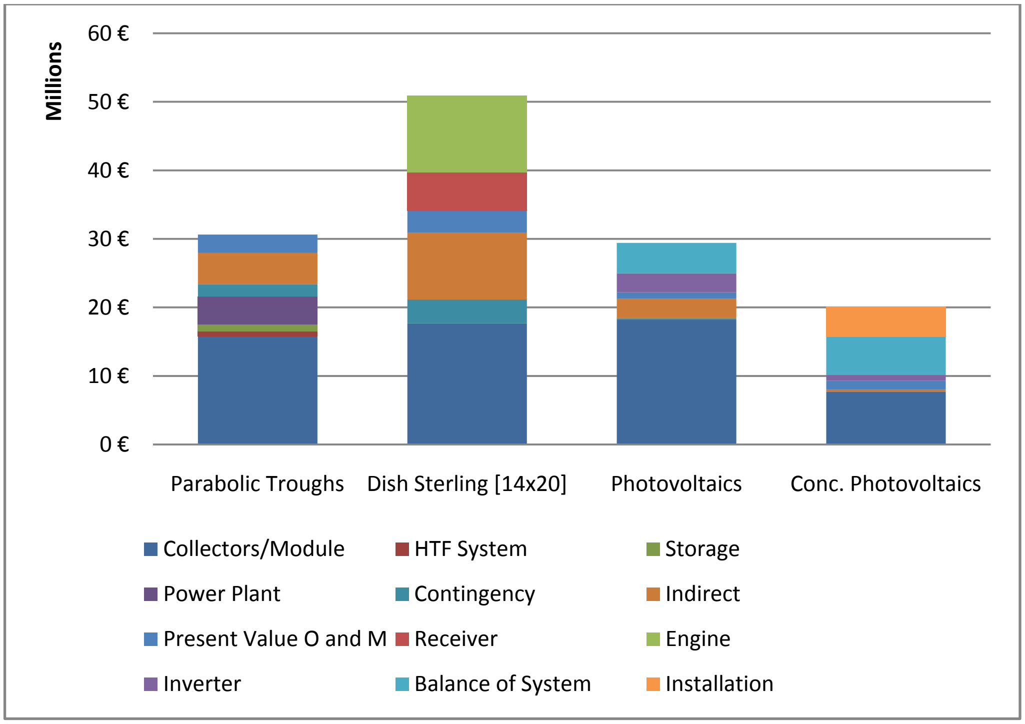


Figure 42, Investment Cost Breakdown and Comparison (65000 square meter).

Appendix B. Mini-Questionnaire

	Carlo Mariani		Kees de Glopper		
OBJECTIVES	Importance	remarks	Importance	Remarks	
Improve Environmental Impact	10		8	*To increase/chnmage over to renewables is one of the DSM Energy targets*	
Reduce Variable Costs	10		5 – 8	*8= On the long run this technology will certainly reduce var. costs*	
Learning Value (about solar power)	6		8	*It is all about getting a demo to run.*	
High Return on Investment	7	*see below*	5 – 8	*See previous answer*	
Reduce Gas Consumption	8		7		
Reduce Electricity Consumption	10		8		
Low Investment Costs	10	*see below*	6		
Low Financial Risk (high predictability of performance and	9		6	*Some Risk is ok*	
PR Value (Employees + Citizens + Authoritities)	10		8	*Should be rewarded by nice subsidies*	
Site appearance to customers	7		7		
Improve Security of Supply	8		5	*Not a real issue/real motivator at this moment?*	
Simplicity of Design	8		6	*Some complexity is allowed*	
Prepare for the future viz. future lack of organic fuels, or high			8	*It is now the time to prepare!*	
CONSTRAINTS	**Value**	**Importance**	**Value**	**Importance**	**Remark**
Maximum Investment Costs	5-6 M€	10	5-20 M€	7	*5M€ for demo project*
Maximum Payback Time	5-7 years	10	5	6	*Not so important for demo pr.*
Minimum Energy Reduction %	25%	10	40%	7	

Assumption:

Carlo Mariani in this case represents DSM Capua

Kees de Glopper & Ans Ligtenbarg represent DSM General

Please answer the question below and grade the items (importance) on a scale of 0-10		
Name: (not neccesary via email)		Ans Ligtenbarg
OBJECTIVES	Importance	
	0-10	Comments?
Improve Environmental Impact	9	
Reduce Variable Costs	8	
Learning Value (about solar power)	10	Is DSM able to define a Demonstration project
High Return on Investment	6	Fit for purpose of demo project
Reduce Gas Consumption	8	Reduce var. cost
Reduce Electricity Consumption	8	Reduce var.cost
Low Investment Costs	7	Fit for purpose of demo project
Low Financial Risk (high predictability of performance and investment) 6 Fit for purpose of demo project		
PR Value (Employees + Citizens + Authoritities)	9	Make sustainability work
Site appearance to customers	6	Do customers visit the site?
Improve Security of Supply	0	Should not be an issue
Simplicity of Design	7	Keep it as simple as possible (maintenance)
…………		
………..		
CONSTRAINTS	Value	Importance(0-10)
Maximum Investment Costs	2-3 mio Euro	10 for demoproject
Maximum Payback Time	5	0 for demoproject
Minimum Energy Reduction %	20%	8 for demoproject

Appendix C. Beam Radiation Comparison

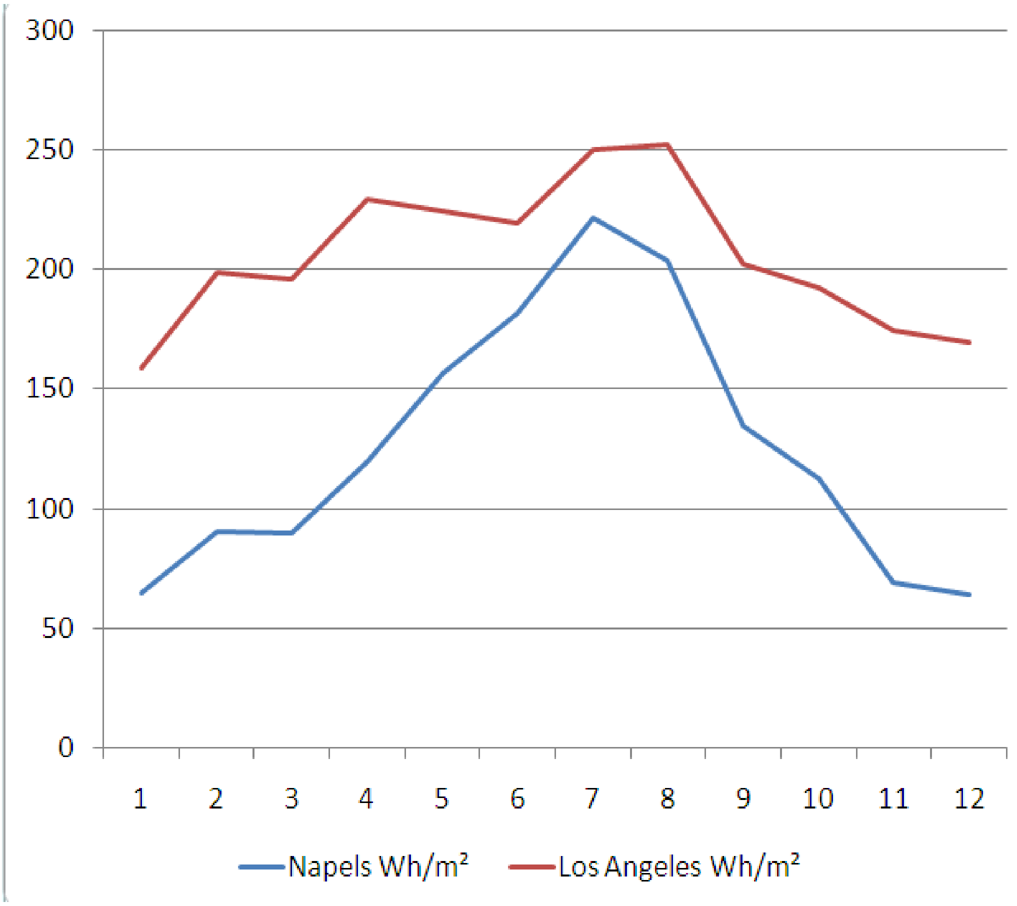
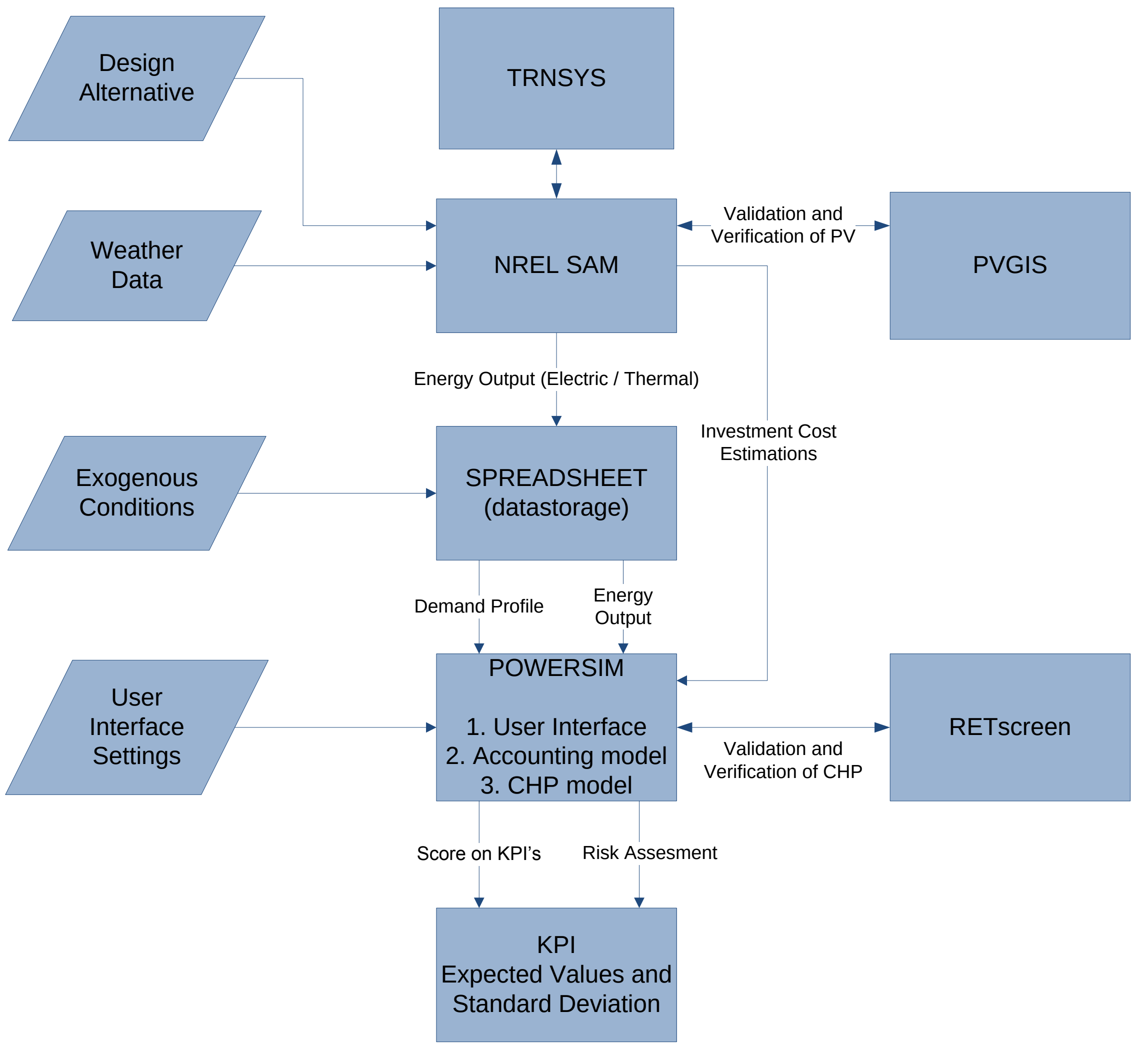


Figure 43, direct normal radiation (beam radiation), monthly averages

Appendix D. Toolbox Details



Filestructure

TRNSYS

TRNSYS is an often used tool for solar energy studies. It is developed by a joint team made up of the Solar Energy Laboratory (SEL) at the University of Wisconsin-Madison, The Centre Scientifique et Technique du Batiment (CSTB) in Sophia Antipolis, France, Transsolar Energietechnik GmbH in Stuttgart, Germany and Thermal Energy Systems Specialists (TESS) in Madison, Wisconsin. (http://www.trnsys.com/, 2009) However it is not freely available for academic use and therfor not directly utilised during this study. The tool however is used indirectly though the use of SAM (solar advisory model). This is a front-end for TRNSYS developed by NREL (National Renewables Energy Labratory based in the USA). NREL is powerfull, easier to use, freely available but somewhat less flexible. The use of TRNYS requires a lot of expertise. Nonetheless detailed modeling of thermodynamic cycles interacting with solar energy using TRNSYS is highly recommended before performing any considerable investment in solar energy.

NREL SAM

The solar advisory model (SAM) developed by the National Renewables Energy Labratory based in the USA, is frequently used during this study. SAM is a front-end for TRNSYS that performs the actual calculations. SAM is set up to calculate the technical performance of various solar energy systems and additionally calculates economic performance. The economic performance of these systems is mainly based on assumptions about tax schemes and incentives that are not applicable outside the USA. And more importantly it assumes that the system operate as stand alone, or grid connected but separate from a industrial facility. Therefoer the tool is only used during this study to calculate the energy output of the design alternatives: electricity or heat output measured over time. The powersim model then uses this as input and simulates the utilisation of this energy if was connected to the facility at Capua. SAM can use weather information in .TMY2 (Typical Meteorological Year) data format. Weather conditions as measured at nearby Napels are used to approximate those of Capua. NREL SAM can freely be obtained via the NREL website. (https://www.nrel.gov/analysis/sam/download.html) SAM can simulate the following technologies: Solar Thermal Electric Generation (STEG) based on Parabolic troughs. Regular PhotoVoltaics, Concentrating Photovoltaics and Parabolic Dish systems. It has a large database with different panels from various manufacturers for each technology type. The STEG simulation is used to calculate the performance of the parabolic troughs only. simulation of the electricity generation and economics are done via the powersim model as at Capua a CHP system is applied. The SAM model cannot (yet) calculate the performance of CHP systems. Inclusion of CHP in the model might make it much more valuable for industrial users but unfortunately, this is not the case.

Appendix E. Toolbox Limitations

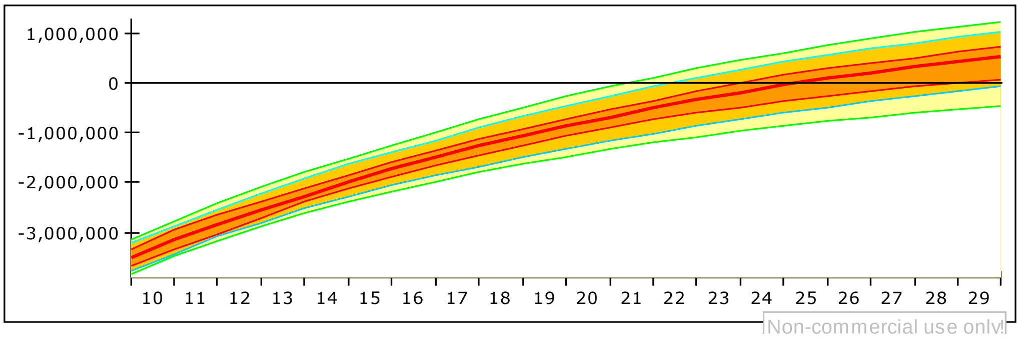
Important factors the model can NOT account for are:

- Hourly variations of price in spot markets (instead daily averages are used) to be exact the model itself can cope with hourly data however the data-set becomes quite big and this slows down simulation runs considerably. Not really a problem for single runs, but disastrous for Monte Carlo simulations (or Latin Hypercube simulations, a hybrid form of Monte Carlo and full-factorial experiment design used by POWERSIM)
- Hourly variation in a design alternatives output. (same as above)
- GHG emissions relative to BAU are only calculated correctly if the simulation period is 20 years.
- Temperature variation in solar energy system heat output. The SAM model yields daily energy output of solar design alternatives in KWh. Although it utilizes temperature variations during internal calculation this information cannot be read without the full commercial TRNSYS package. The energy output is used to calculate how much NG or electricity consumption is displaced. However if the volume of medium or low temperature water produced by the solar system becomes too large the system can no longer utilize it, regardless of energy content. Thus the estimations used throughout this research for solar heat utilization are only trustworthy when the solar energy system is undersized. The POWERSIM model allows the user to limit the amount of energy that any solar energy alternative is allowed to contribute to the boiler or CHP system. It is set to 20% throughout this research. Keep in mind that larger contributions could be favorable but analyzing this falls outside the scope of this research and requires detailed thermodynamic simulations.
- Limited usability of heat from solar panels used for in a CHP system. The model assumes that all heat that is produces via PT solar panels can be used by the CHP system and thereby abate NG usage. However this is only reasonable as long as The scale of the PT field is undersized compared to the CHP. At larger scales the PT field delivers medium temperature heat in high volumes but this can no longer be used by the CHP system as the steam-flow trough the CHP system is limited. Oversizing would thus result in waste heat only. The model is not able to determine the scale of the PT field which is still acceptable. For this further research into the thermodynamics of such a system is needed and the only remedy within scope is simply to choose small scales rather arbitrarily. This is a important limitation of the research as far as solar assisted CHP is concerned!

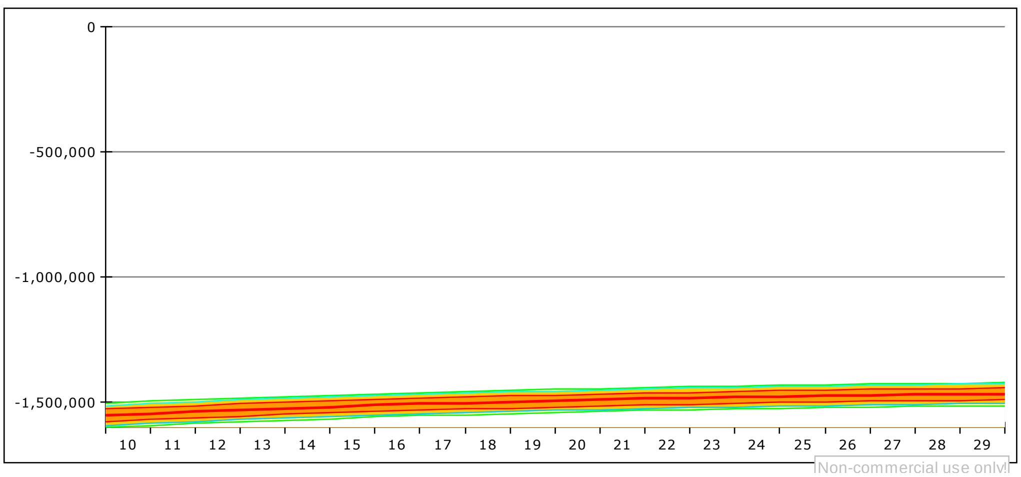
- Non-linear scaling of investment costs. Investment costs of design alternatives are scaled linearly with size and capacity. This is a reasonable approximation as long as the scales are chosen sensibly. For PV the scale should not be chosen below 200.000 Euros of investment. For CHP the scale should not be chosen below 3 MW. Otherwise investment costs should be reexamined closely.
- Non linear scaling of investment costs when combining options. Combining design alternatives and examining result is possible within the model. However interaction effects considering investment costs are not accounted for. However interaction effects due to utilization of waste heat for example are accounted for! (for example when lowering consumption of HEAT and simultaneously investing in CHP the model accounts for the fact that the CHP -heat can be utilized only to a lower maximum amount)
- Energy Prices as a function of volume and consumption profile. Energy prices can be effected by the volume and load profile of the Capua site. Buying larger volumes or a more stable load profile often result in lower prices. This is not accounted for. (YET XXX)
- Variable turbine-generator efficiency as function of load. The model does not account for a efficiency that is dependent on load. In reality efficiency is often best at full load. (XXX Duffie)
- Interrelationship between maintenance costs and efficiency gains. Higher efficiencies can often be achieved by a solar power system when it is more thoroughly cleaned. The model does not account for any relationship between maintenance costs and efficiency.

Appendix F. Monte Carlo Simulation Output.

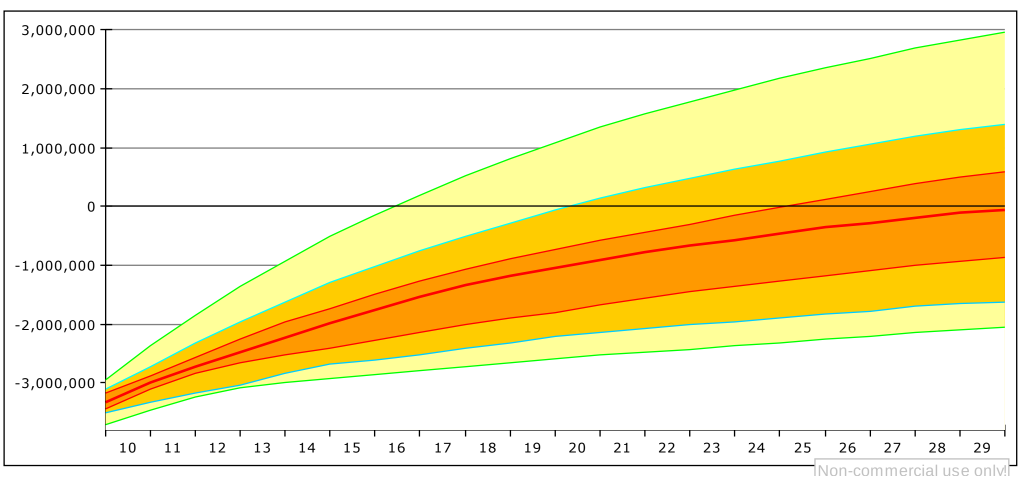
PV



PTC

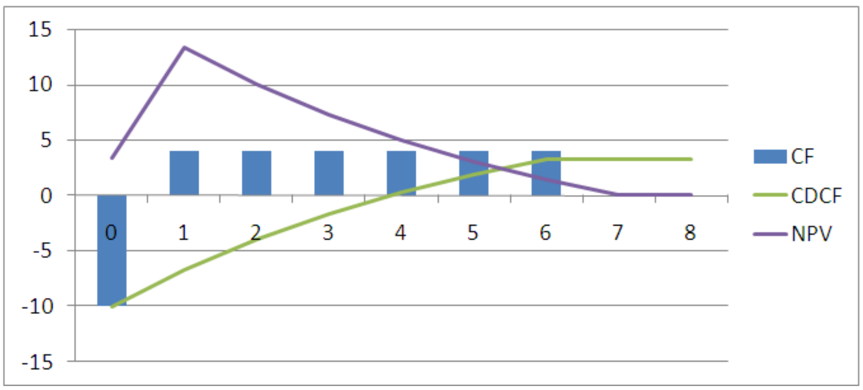


SA-CHP



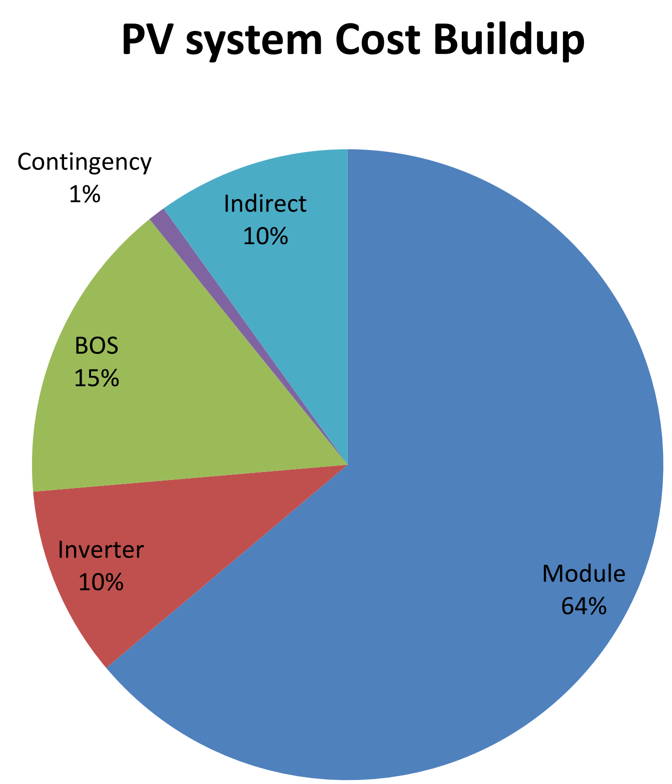
Appendix G. NPV vs. CDCF

The difference between CDCF and NPV is illustrated by the fact that after an investment is made the present value of the system should immediately rise as the site itself has gained in value due to the investment, whereas the CDCF displays a drop of cash balance due to the unrecovered investment. In other words: due to the investment the expected future cash flows are higher and thus so is the present value of those cash flows (CF). If the project has limited lifetime the NPV would diminish over time as there are fewer and fewer future cash flows left. The CDCF on the other hand shows the drop in cash when the investment is made, and the rise of cash when income is generated by that investment. The discount rate devalues these future cash flows but they increase the CDCF nonetheless.



Graphs of the CDCF are more intuitive then NPV and therefore used as a performance indicator. The value of the CDCF at the end of the lifetime of the project is equal to the net present value of the project at t=0, this is because at that point all discounted cash flows are added to the initial investment costs! This is illustrated by the figure. Thus simply look at the value of the CDCF at the end of the Time Series to immediately know the NPV of that project at t=0. And look at the development of the CDCF over time to understand how the project generates (discounted) cash over time. If the aim was to understand what a potential buyer would be willing to pay for the site over time, with and without an investment, NPV would be a better indicator.

Appendix H. Capital Cost Buildup PV System



Appendix I. Market Data, Italy

TAB. 1.14

Final electricity prices for industrial consumers

Prices net and gross of taxes; July-December 2007; c€/kWh

MWh/year	< 20		20-500		500-2.000		2.000-20.000		20.000-70.000		70.000-150.000	
	Net	Gross	Net	Gross	Net	Gross	Net	Gross	Net	Gross	Net	Gross
Austria	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Belgium	13.11	17.38	10.79	14.35	8.53	11.49	7.48	10.20	6.62	8.82	5.69	7.44
Bulgaria	6.75	8.13	6.34	7.67	5.62	6.80	5.01	6.08	4.24	5.16	3.83	4.70
Cyprus	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Denmark	8.70	22.04	8.35	21.62	7.65	20.74	7.61	20.68	7.08	20.02	7.08	20.02
Estonia	6.71	8.12	5.62	6.77	5.18	6.26	4.35	5.30	3.32	4.09	3.32	4.03
Finland	7.36	9.26	6.53	8.25	5.63	7.15	5.38	6.85	4.05	5.22	4.17	5.37
France	9.60	11.89	6.64	8.67	5.24	6.92	4.68	6.31	4.68	6.48	4.33	6.00
Germany	14.79	21.52	10.94	16.14	8.94	13.53	7.76	12.10	7.24	10.84	7.22	11.13
Greece	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Ireland	15.43	17.51	13.85	15.69	12.35	13.88	10.86	12.00	10.94	12.02	10.26	11.17
Italy	***15.04***	***22.22***	***12.05***	***17.52***	***11.60***	***16.04***	***10.55***	***14.04***	***7.20***	***9.42***	***7.20***	***9.42***
Latvia	13.03	15.38	7.17	8.46	5.94	7.01	4.99	5.88	4.47	5.28	4.30	5.07
Lithuania	9.88	11.65	8.34	9.84	7.20	8.50	5.95	7.03	5.31	6.27	5.05	5.95
Luxembourg	15.54	16.81	11.04	12.04	9.99	10.93	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Malta	13.07	13.72	12.89	13.54	12.21	12.82	9.17	9.63	5.81	6.10	n.a.	n.a.
The Netherlands	18.00	26.00	10.00	14.00	9.00	12.00	8.00	10.00	8.00	10.00	8.00	9.00
Poland	13.51	17.39	10.03	13.03	8.43	11.04	6.26	8.46	4.70	6.52	4.35	7.47
Portugal	10.41	13.03	9.55	11.37	7.79	9.11	6.98	8.18	5.62	6.78	4.97	6.08
United Kingdom	13.94	16.82	11.59	14.21	10.33	12.67	9.06	11.10	8.65	10.43	8.24	9.93
Czech Republic	14.13	16.83	10.92	13.00	9.46	11.28	7.78	9.24	6.68	7.96	6.68	7.96
Romania	12.09	14.41	10.67	12.73	9.08	10.84	7.90	9.44	6.38	7.63	5.72	6.84
Slovakia	14.48	17.22	12.54	14.92	10.48	12.48	9.52	11.34	8.48	10.09	7.34	8.75
Slovenia	12.15	15.38	10.66	13.27	8.72	10.92	7.09	8.97	6.16	7.77	6.45	8.15
Spain	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Sweden	9.49	9.54	7.53	7.59	6.51	6.56	5.77	5.82	5.21	5.26	5.08	5.13
Hungary	10.89	14.64	11.18	14.98	9.97	13.54	8.62	11.92	7.23	10.25	5.90	8.65
Croatia	9.16	11.34	7.79	9.70	7.24	9.02	6.15	7.65	4.51	5.74	3.96	4.92
Norway	7.13	10.51	6.41	9.60	6.28	9.45	5.14	8.02	4.06	6.66	1.95	4.03
European Union(A)	12.95	17.41	9.95	13.46	8.59	11.60	7.55	10.23	6.61	8.88	6.38	8.67

A) Average price relating to the European Union (23 countries) weighted with national industrial consumption for 2004.

Source: AEEG calculations on Eurostat data.

TAB. 1.15

Final natural gas prices for domestic consumers

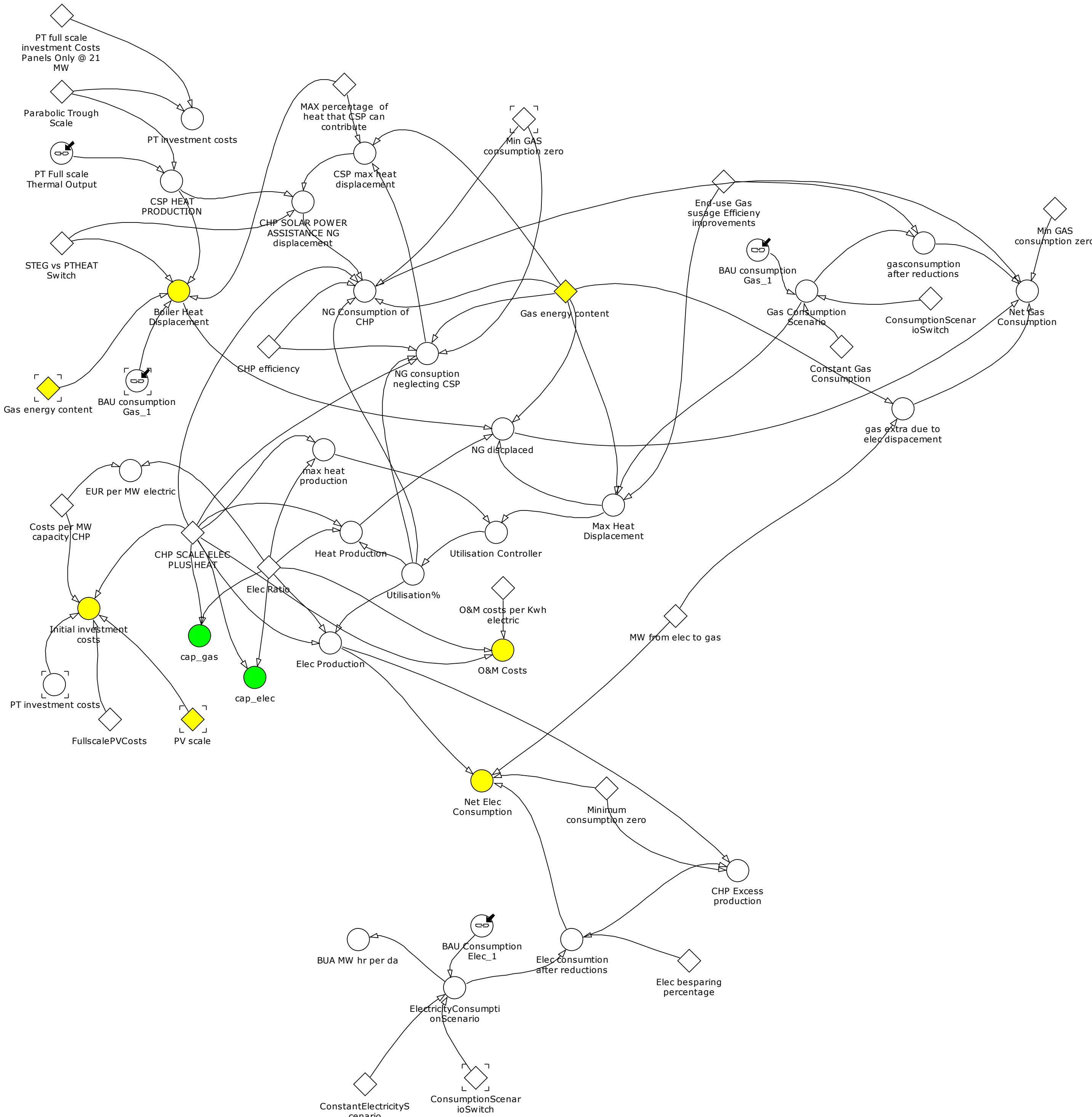
Prices net and gross of taxes; July-December 2007; c€/m^3

m^3/year	< 525,36		525,36-5.253,60		>= 5.253,60	
	Net	Gross	Net	Gross	Net	Gross
Austria	59.65	79.68	47.13	64.53	40.66	56.76
Belgium	66.43	86.61	42.52	58.47	37.95	50.02
Bulgaria	27.02	32.41	28.48	34.18	28.92	34.73
Cyprus	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Denmark	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Estonia	34.59	40.81	23.51	27.81	23.38	27.59
Finland	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
France	86.57	99.25	46.37	54.44	40.66	48.27
Germany	67.46	98.90	48.27	64.87	45.30	61.29
Greece	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Ireland	101.07	114.70	56.49	64.15	48.65	55.20
Italy	58.60	74.80	42.80	65.90	39.30	65.50
Latvia	29.76	35.15	27.91	32.92	27.75	32.76
Lithuania	32.26	38.07	21.03	24.82	18.53	21.87
Luxembourg	51.36	67.84	37.23	41.69	37.23	41.23
Malta	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
The Netherlands	75.72	109.83	45.45	73.78	42.75	69.40
Poland	44.70	54.53	34.78	42.43	31.89	38.92
Portugal	83.91	88.11	65.73	69.02	53.84	56.53
United Kingdom	38.94	40.89	35.93	37.73	31.09	32.64
Czech Republic	36.71	43.69	31.99	38.07	31.56	37.56
Romania	24.14	36.61	24.03	36.19	24.05	35.48
Slovakia	72.20	85.92	36.83	43.83	36.34	43.24
Slovenia	55.96	70.77	42.29	54.32	40.54	52.23
Spain	63.39	73.54	53.00	61.47	43.34	50.27
Sweden	70.79	117.32	54.74	97.30	53.92	96.27
Hungary	33.50	40.20	33.69	40.42	33.26	39.91
Croatia	22.57	28.95	22.57	28.95	22.57	28.95
Norway	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
European Union(A)	58.70	74.85	42.16	54.48	38.26	50.46

(A) Average price relating to the European Union (22 countries) weighted with national domestic consumption for 2004.

Source: AEEG calculations on Eurostat data.

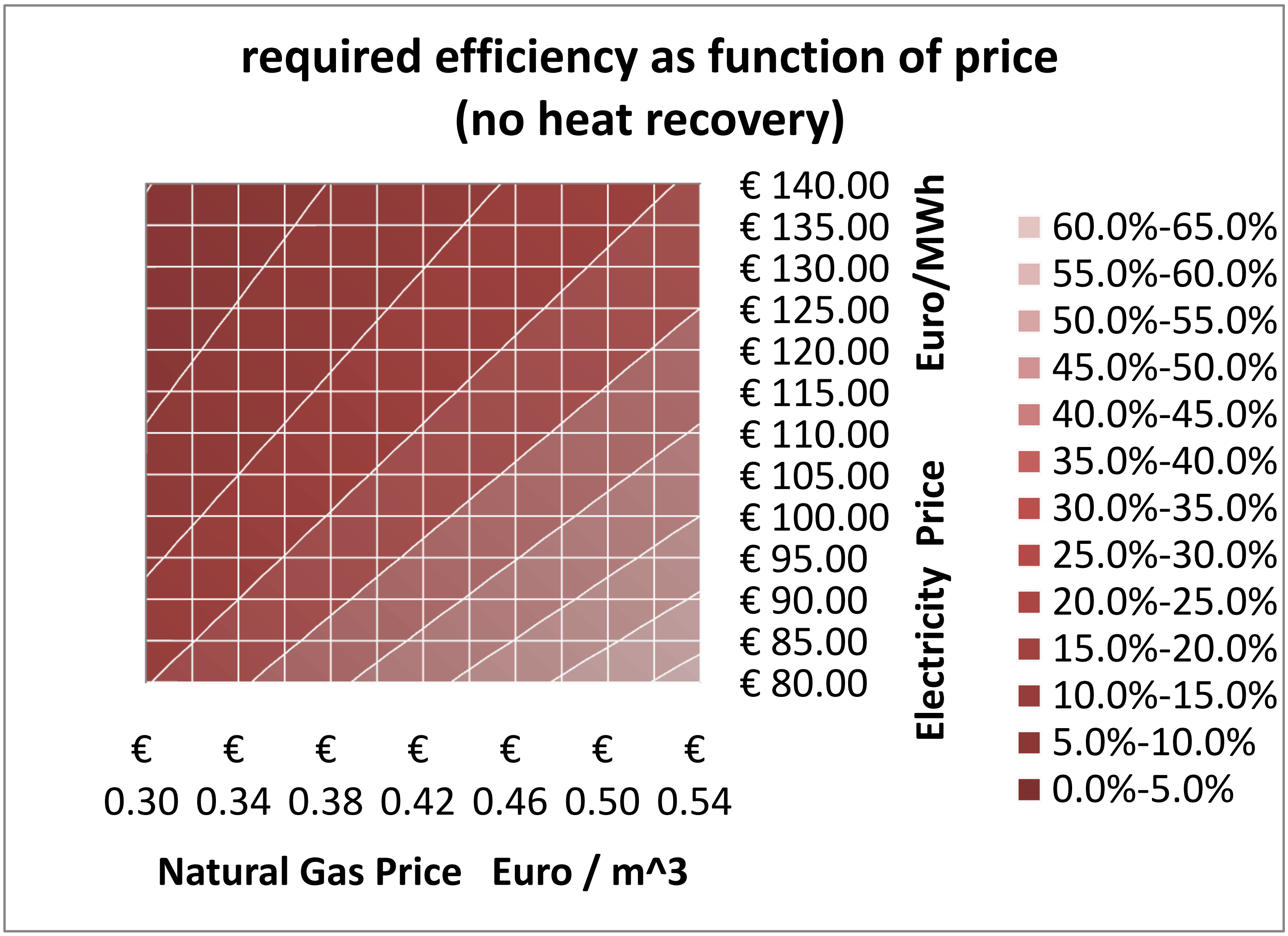
Appendix J. Powersim CHP model Details



Appendix K. Energy Prices, efficiency and Electricity generation from Natural Gas

The graph illustrates the minimum efficiency that is required for the conversation of natural gas into electricity (without waste heat recovery) in order for the system to generate a positive cash flow, as a function of electricity and natural gas price. Ignoring all other costs.

For example at low NG prices and high Electricity prices only very low efficiencies are required to generate a positive cash flow.



Appendix L. Powersim Model Equations

Name	Unit	Definition
BALANCE CDCF	EUR	'Initial investment costs'
BALANCE CDCF.Elec_cost_D_cash flow.out		Elec_cost_D_cash flow
BALANCE CDCF.Feedback_D_ cash flow.in		'Feedback_D_ cash flow'
BALANCE CDCF.Gas_cost_D_cash flow.out		Gas_cost_D_cash flow
BALANCE CDCF.Investment cost_D_cash flow.out		'Investment cost_D_cash flow'
Electricity Costs	EUR	0
Electricity Costs.Elec_cost_D_cash flow.in		Elec_cost_D_cash flow
End Electriciy Import	MW*hr	0
End Electriciy Import.Rate_1.in		Rate_1
End Gas Import	m^3	0
End Gas Import.Rate_2.in		Rate_2
Gas Costs	EUR	0
Gas Costs.Gas_cost_D_cash flow.in		Gas_cost_D_cash flow
Investment Costs and O&M	EUR	0
Investment Costs and O&M.Investment cost_D_cash flow.in		'Investment cost_D_cash flow'
NONdiscounted elec costs	EUR	0
NONdiscounted elec costs.Rate_3.out		Rate_3

NONdiscouted gas costs	EUR	0
NONdiscouted gas costs.Rate_4.out		Rate_4
Total feedback income	EUR	0
Total feedback income.Feedback_D_ cash flow.out		'Feedback_D_ cash flow'
Auxiliary_1	%	100%-(('NONdiscounted elec costs'+'NONdiscouted gas costs')/'Simulation period in years') / ('BAU Average yearly Variable Gas Costs'+'BAU Average yearly Variable electricity Costs')
Average Variable electricity Costs reduction	%	100%-('NONdiscounted elec costs'/'Simulation period in years')/'BAU Average yearly Variable electricity Costs'
Average Variable gas Cost reduction	%	100%-('NONdiscouted gas costs'/'Simulation period in years')/'BAU Average yearly Variable Gas Costs'
BAU Average yearly Variable electricity Costs	EUR/Syear	-5089251.64
BAU Average yearly Variable Gas Costs	EUR/Syear	-1830754.82
BAU CO2 Constant	kg	758436808
BAU Consumption Elec_1	(kW*hr)/da	0
BAU consumption Gas_1	m^3/da	0
BAU yearly elec consumption	MW	-879039.332<<(MW*hr)>>/20<<Syear>>
BAU yearly NG consumption	m^3/Syear	-94522360.00<<m^3>>/20<<Syear>>

Boiler Heat Displacement	W	(1-'STEG vs PTHEAT Switch')*MIN('BAU consumption Gas_1'*'MAX percentage of heat that CSP can contribute'*'Gas energy content','CSP HEAT PRODUCTION')
BUA MW hr per da	MW	ElectricityConsumptionScenario
cap_elec	MW	'CHP SCALE ELEC PLUS HEAT'*'Elec Ratio'
cap_gas	MW	'CHP SCALE ELEC PLUS HEAT'*(1-'Elec Ratio')
CHP efficiency	%	95
CHP Excess production	MW	MAX('Elec Production'-'Elec consumtion after reductions','Minimum consumption zero')
CHP SCALE ELEC PLUS HEAT	MW	1E-12
CHP SOLAR POWER ASSISTANCE NG displacement	MW	'STEG vs PTHEAT Switch'* MIN('CSP HEAT PRODUCTION','CSP max heat displacement')
CO2 emission Elec	T	'CO2 per Mwh'*'End Electriciy Import'
CO2 emmission NG	kg	'End Gas Import'*'CO2 per m NG'
CO2 equivelant Price	EUR/T	-'Initial investment costs'/'total CO2 eq'
CO2 per m NG	kg/m^3	1.78
CO2 per Mwh	kg/(kW*hr)	0.6714
CO2 Reduction Investment Efficiency	kg/EUR	'total CO2 eq'/'BALANCE CDCF'
Constant Gas Consumption	m^3/da	12815
ConstantElectricityScenario	(kW*hr)/da	120150
ConsumptionScenarioSwitch		0
Copy of Discount Rate		1/(1+Inflation+'Risk Factor')^(YEAR(TIME)-YEAR(STARTTIME))

Costs per MW capacity CHP	EUR/MW	-400000
CSP Feedback Elec	(kW*hr)/da	0
CSP feedback Tarif	EUR/(kW*hr)	0.25
CSP HEAT PRODUCTION	MW	'PT Full scale Thermal Output'*'Parabolic Trough Scale'
CSP max heat displacement	kW	'MAX percentage of heat that CSP can contribute'*('NG consuption neglecting CSP'*'Gas energy content')
Discount Rate		1/(1+Inflation+'Risk Factor')^(YEAR(TIME)-YEAR(STARTTIME))
Elec besparing percentage	%	0
Elec consumtion after reductions	kW	ElectricityConsumptionScenario*(100%-'Elec besparing percentage')
Elec Price	EUR/(kW*hr)	0.15
Elec Price_1	EUR/(kW*hr)	0
Elec Production	MW	'CHP SCALE ELEC PLUS HEAT'*'Elec Ratio'*'Utilisation%'
Elec Ratio	%	23
Elec_cost_D_cash flow	EUR/da	(('Net Elec Consumption'-'BAU Consumption Elec_1')*'Elec Price')*'Discount Rate'
Electricity consumption reduction % of BAU	%	('End Electriciy Import'/'Simulation period in years')/'BAU yearly elec consumption'
Electricity Costs_	EUR	-'Electricity Costs'
ElectricityConsumptionScenario	kW	(ConstantElectricityScenario*ConsumptionScenarioSwitch)+(1-ConsumptionScenarioSwitch)*'BAU Consumption Elec_1'

End-use Gas susage Efficieny improvements	%	0
EUR per MW electric	EUR/MW	'Costs per MW capacity CHP'*(1/'Elec Ratio')
feed-in tarif as percentage of elec Price	%	85
Feedback_D_ cash flow	EUR/da	'Sell Electricity income'+(('CSP Feedback Elec'*('CSP feedback Tarif'+'Elec Price_1'))+(PVoutputtotal*'PV feedback Tarif'))*'Discount Rate'
FullscalePVCosts	EUR	-35000000
Gas Consumption Scenario	m^3/da	ConsumptionScenarioSwitch*'Constant Gas Consumption'+(1-ConsumptionScenarioSwitch)*'BAU consumption Gas_1'
Gas Costs_	EUR	-'Gas Costs'
Gas energy content	(kW*hr)/m^3	10.8
gas extra due to elec dispacement	m^3/hr	'MW from elec to gas'/'Gas energy content'
Gas Price_1	EUR/m^3	0.37
Gas_cost_D_cash flow	EUR/da	('Gas Price_1'*('Net Gas Consumption'-'BAU consumption Gas_1'))*'Discount Rate'
gasconsumption after reductions	m^3/da	'Gas Consumption Scenario'*(100%-'End-use Gas susage Efficieny improvements')
Graph0		0
Heat Production	MW	'CHP SCALE ELEC PLUS HEAT'*(1-'Elec Ratio')*'Utilisation%'
Inflation	%	4
Initial investment costs	10^6 EUR	'CHP SCALE ELEC PLUS HEAT'*'Costs per MW capacity CHP'+(FullscalePVCosts*'PV scale')+'PT investment costs'

Insurance Cost % of investment-Costs	%/Syear	0.5
Investment cost_D_cash flow	EUR/da	(('Initial investment costs'*'Insurance Cost % of investment-Costs')+('O&M Costs'+'Investment costs not at year zero'))*'Discount Rate'
Investment costs not at year zero	EUR/da	0
Irradiation Uncertainty Factor	%	100
Max Heat Displacement	MW	((100<<%>>-'End-use Gas susage Efficieny improvements')*'Gas Consumption Scenario')*'Gas energy content'
max heat production	MW	'CHP SCALE ELEC PLUS HEAT'*(1-'Elec Ratio')
MAX percentage of heat that CSP can contribute	%	25%
Min GAS consumption zero	m^3/da	0
Minimum consumption zero	(kW*hr)/da	0
MW from elec to gas	MW	0
Net Elec Consumption	(kW*hr)/da	MAX('Elec consumtion after reductions'-'Elec Production','Minimum consumption zero')-'MW from elec to gas'
Net Gas Consumption	m^3/da	MAX('gasconsumption after reductions'-'NG discplaced','Min GAS consumption zero')+'NG Consumption of CHP'+'gas extra due to elec dispacement'
NG Consumption of CHP	m^3/hr	MAX(((('CHP SCALE ELEC PLUS HEAT'*'Utilisation%')-'CHP SOLAR POWER ASSISTANCE NG displacement')/'Gas energy content')/'CHP efficiency','Min GAS consumption zero')

NG consumption Reduction % of BAU	%	(('End Gas Import')/'Simulation period in years')/'BAU yearly NG consumption'
NG consuption neglecting CSP	m^3/hr	MAX((('CHP SCALE ELEC PLUS HEAT'*'Utilisation%')/'Gas energy content')/'CHP efficiency','Min GAS consumption zero')
NG discplaced	m^3/hr	MIN('Heat Production'+'Boiler Heat Displacement','Max Heat Displacement')/'Gas energy content'
O&M Costs	EUR/hr	('Elec Ratio'*'CHP SCALE ELEC PLUS HEAT')*'O&M costs per KWh electric'
O&M costs per KWh electric	EURC/(kW*hr)	2
Other Price scenario	EUR/(kW*hr)	0
Parabolic Trough Scale	%	0
PT full scale investment Costs Panels Only @ 21 MW	EUR	-15000000
PT Full scale Thermal Output	MW	0
PT investment costs	EUR	'Parabolic Trough Scale'*'PT full scale investment Costs Panels Only @ 21 MW'
PV Efficiency Uncertainty Factor	%	100
PV feedback Tarif	EUR/(kW*hr)	0.37
PV scale	%	0
PV_outputA	kW	0
PVoutputtotal	kW	PV_outputA*'Irradiation Uncertainty Factor'*'PV Efficiency Uncertainty Factor'*'PV scale'
Rate_1	(kW*hr)/da	('Net Elec Consumption'-'BAU Consumption Elec_1')-PVoutputtotal

Rate_2	m^3/da	'Net Gas Consumption'-'BAU consumption Gas_1'
Rate_3	EUR/da	'Net Elec Consumption'*'Elec Price'
Rate_4	EUR/da	'Gas Price_1'*'Net Gas Consumption'
Risk Factor	%	11
Sell Electricity income	EUR/da	'CHP Excess production'*('Elec Price_1'+'Other Price scena-rio')*'feed-in tarif as percentage of elec Price'
Simulation period in years	Syear	(STOPTIME-STARTTIME)
STEG vs PTHEAT Switch		1
total CO2 eq	T	-'CO2 emission Elec'+'CO2 emmission NG'
Total CO2 Output Percentage of BAU	%	'total CO2 eq'/'BAU CO2 Constant'
Utilisation Controller	%	MAX(MIN(100<<%>>,'Max Heat Displacement'/'max heat production'),10<<%>>)
Utilisation%	%	'Utilisation Controller'

Appendix M. Alternative Model Approach